Chapter 1

Electric Forces and Fields

Electric and Magnetic Phenomena

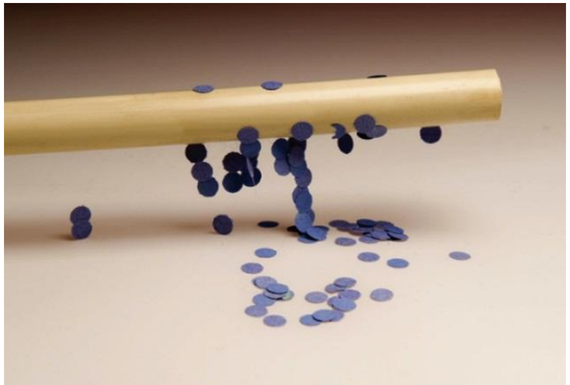
- Electric and magnetic forces act on electric charges and currents
- Electric charges and currents also act as sources of electric and magnetic fields
- Electricity and magnetism are really a single unified phenomena
  - Called electromagnetism
  - Leads to a theory of electromagnetic radiation
    - Light is an example
    - Electromagnetism forms the basis for the study of optics

Observational Facts

- Discovery of electricity is generally credited to the Greeks
  - About 2500 years ago
- They observed electric charges and the forces between them in many situations
- Used amber
  - A type of dried tree sap
  - After amber is rubbed with a piece of animal fur, the amber can attract small pieces of dust

Observational Facts, cont.

- The Greek word for amber was “elektron” from which we get the words electron and electricity (A)
- Modern experiments use plastic and paper (B)
- The force occurs even when the plastic and paper are not in contact (C)

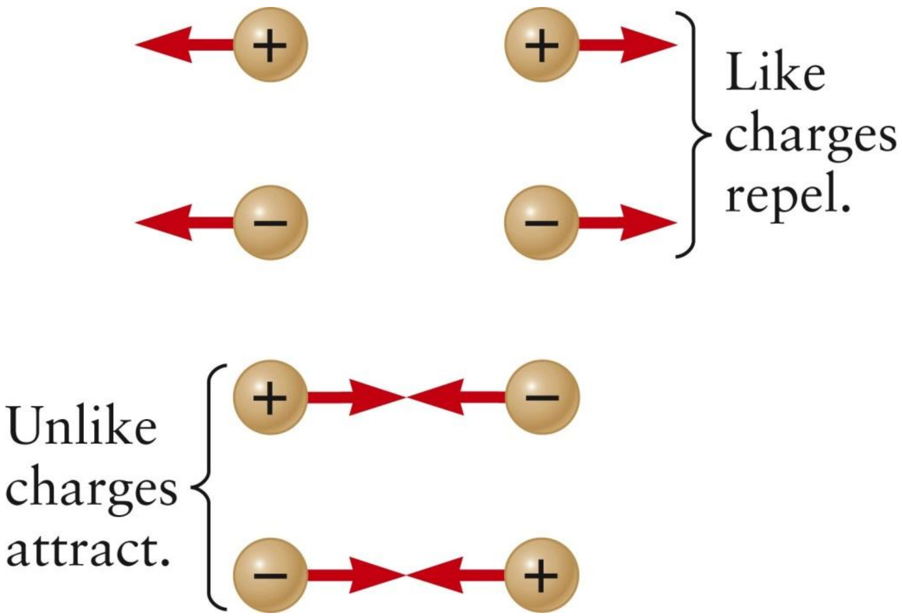


Basic Properties of Charges

- There are two types of electric charges
  - They are called positive and negative
  - Protons have positive charges
  - Electrons have negative charges
- Charge comes in quantized units
  - All protons carry the same amount of charge, +e
  - All electrons carry the same amount of charge, -e

Basic Properties, cont.

- Like charges repel each other, unlike charges attract
  - Like charges – both positive or both negative
  - Unlike charges – one positive and one negative
  - The "like" and "unlike" apply to the signs of the charges, not their magnitudes



Basic Properties, final

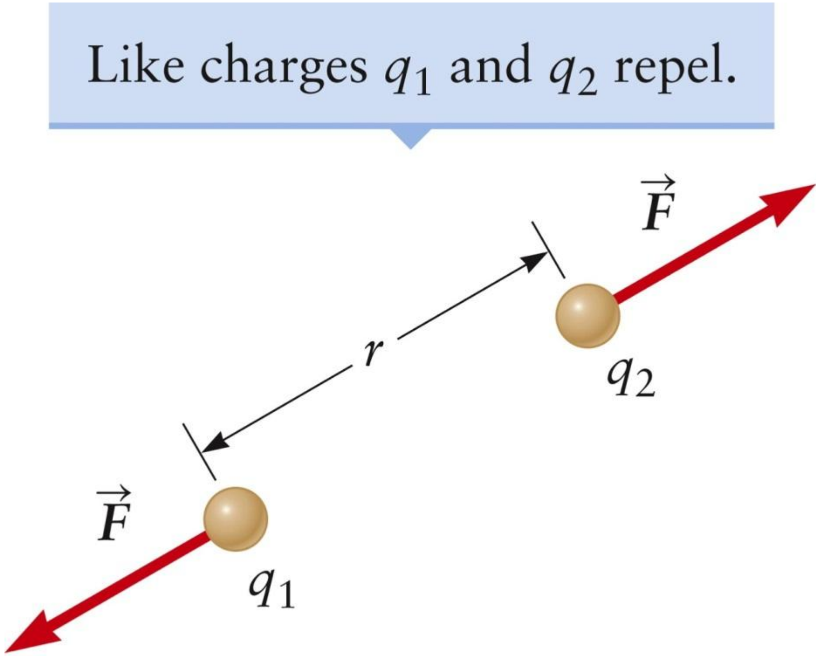
- Charge is conserved
  - The total charge on an object is the sum of all the individual charges carried by the object
  - Charge can move from place to place, and from one object to another, but the total charge of the universe does not change

What is Electric Charge?

- Charge is a fundamental property of matter
  - The amount of charge on a particle determines how the particle reacts to electric and magnetic fields
  - An actual definition is not possible
- The SI unit of charge is the **Coulomb**
  - In honor of Charles de Coulomb
- Electron charge = $-e = -1.6 \times 10^{-19}$ C
- Proton charge = $+e = +1.6 \times 10^{-19}$ C
- The symbol *e* is used to denote the magnitude of the charge on an electron or proton
- The symbols *q* and *Q* are used to denote charge in general

Electric Forces and Coulomb's Law

- Electric force can be attractive or repulsive
- It is very large
- Assume two charged particles can be modeled as point particles
- The magnitude of the electric force between the two particles is given by Coulomb's Law



COULOMB'S LAW:

$$|\vec{F}| = \frac{kq_1q_2}{r^2} = \frac{q_1q_2}{4\pi\varepsilon_0 r^2}$$

Coulomb's Law

- Coulomb's Law says the magnitude of the force between two electric charges is given by

$$F = k\frac{q_1 q_2}{r^2}$$

- The constant k = 8.99 x 10^9 N · m^2 / C^2
- The direction of the force is along the line that connects the two charges
- A repulsive force will give a positive value for F
  - Between like charges
- An attractive force will give a negative value for F
  - Between unlike charges

Coulomb's Law – Alternative

- Another way to write Coulomb's Law is

$$F = \frac{q_1 q_2}{4\pi \varepsilon_o r^2}$$

  - ε_o is another constant
  - It is called the permittivity of free space
  - It is equal to $8.85 \times 10^{-12}\ C^2 / N \cdot M^2$
- The constants are related through

$$k = \frac{1}{4\pi\varepsilon_o}$$

  - Either form can be used to calculate the force between two particles

Features of Coulomb's Law

- The form of Coulomb's Law is similar to Newton's Law of Universal Gravitation
  - Both laws exhibit a $1/r^2$ dependence on the separation between particles
  - A negative charge can move in a circular orbit around a positive charge
    - This was the early model for the atom
  - Gravity is always attractive
  - Electric forces may be attractive or repulsive

Features of Coulomb's Law, cont.

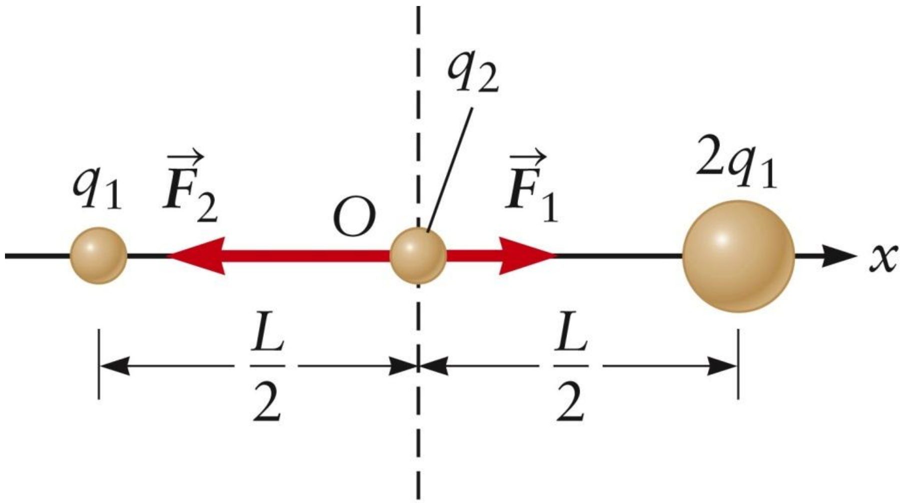
- The value of F given by Coulomb's Law is the magnitude on each of the particles
  - A force of F is exerted on q_1 and a force of equal magnitude and opposite direction is exerted on q_2
    - Newton's Third Law action-reaction pair

Size of the Electric Force

- Assume you have two boxes each containing one gram of electrons
- There would be 1.1×10^{27} electrons in each box
- The force between the boxes would be 3×10^{26} N
  - This is almost a million times larger than the force between the Sun and the Earth
- Ordinary matter consists of approximately equal numbers of electrons and protons
  - With equal numbers, $Q_{total} = 0$ and $F = 0$

Superposition of Forces

- When there are more than two charges in a problem, the ***principle of superposition*** must be used
- Find the forces on the charge of interest due to all the other forces
- Add the forces as vectors



Problem Solving Strategy

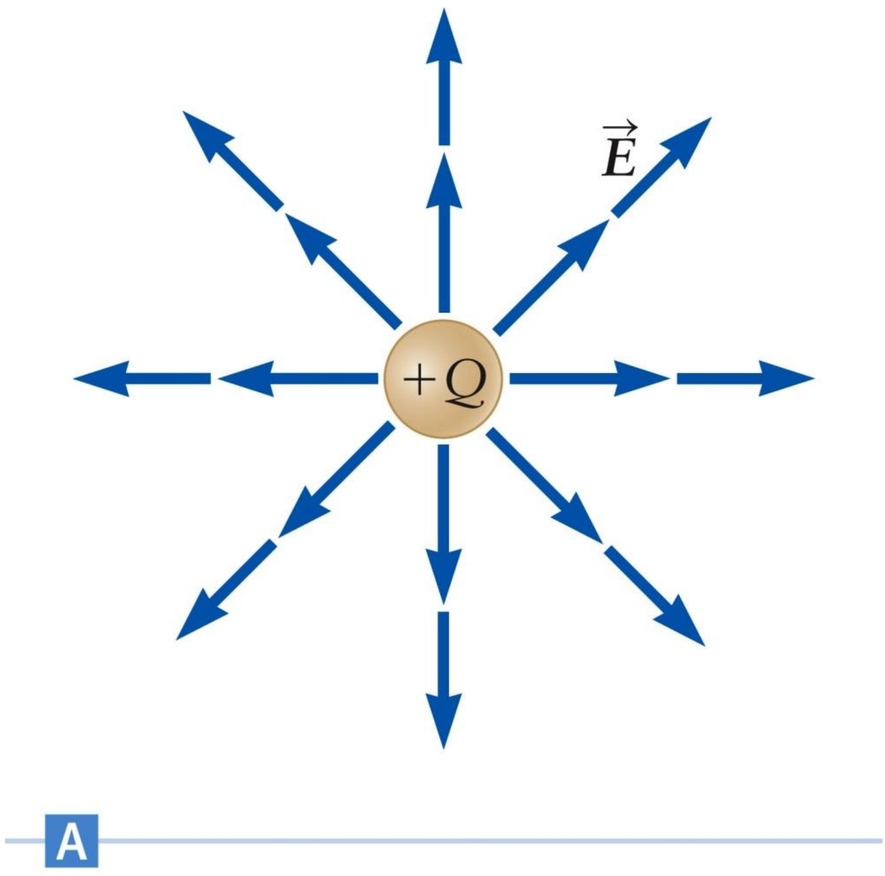
- ***Recognize the principle***
  - The electric force can be found using Coulomb's Law
  - The principle of superposition may also be needed
- ***Sketch the problem***
  - Construct a drawing and show the location and charge of each object
    - Include a coordinate system
  - Include the directions of all the electric forces acting on the particle of interest

Problem Solving Strategy, cont.

- ***Identify the relationships***
  - Use Coulomb's Law to find the magnitudes of the forces acting on the particle of interest
- ***Solve***
  - The total force on a particle is the sum of all the individual forces
  - Add the forces as vectors
  - It is usually easier to work in terms of the components along the coordinate system
- ***Check***
  - Consider what the answer means
  - Check if the answer makes sense

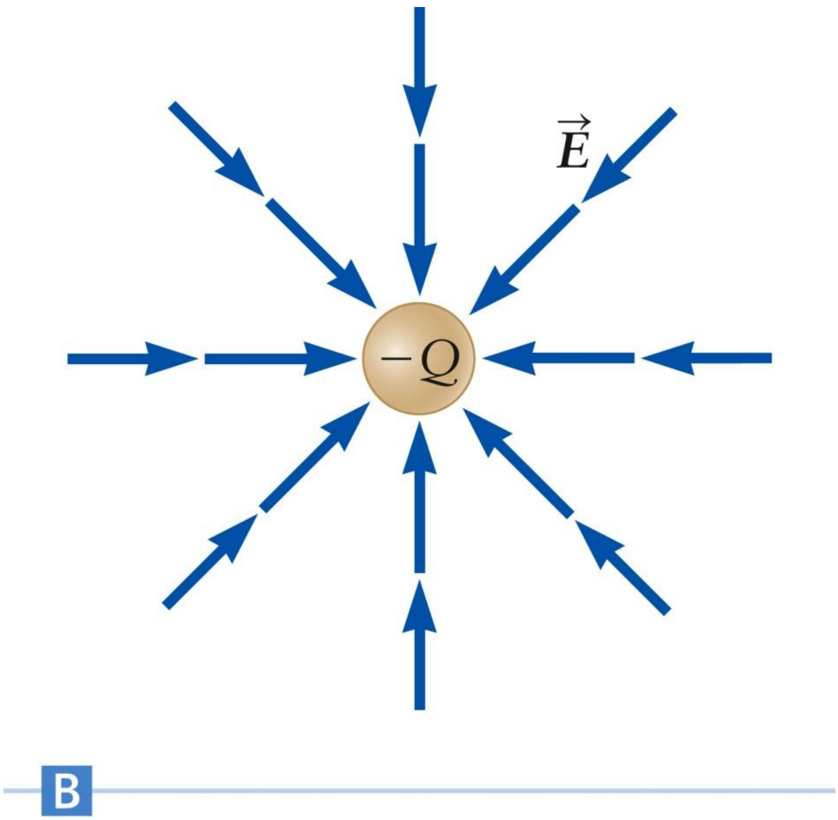
Electric Field

- An electric field gives another explanation of electric forces
- The presence of a charge produces an electric field
  - Shown by the arrows in the figure
- The electric field is similar to the gravitational field near an isolated mass



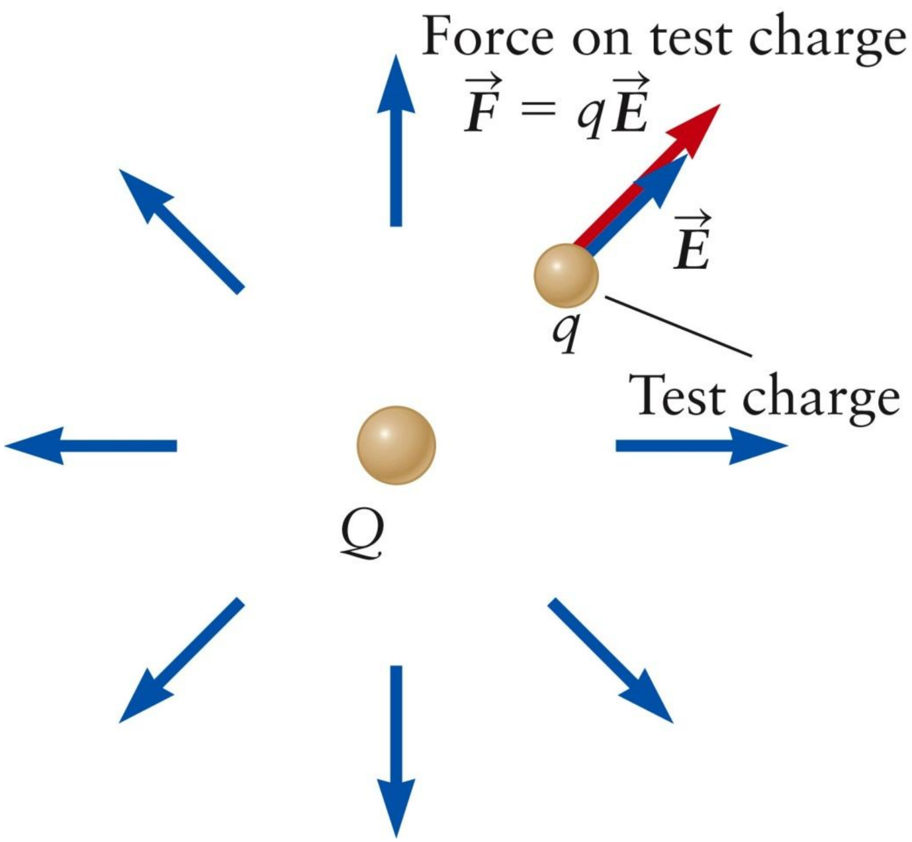
Electric Field, cont.

- A positive charge produces field lines that radiate outward
- For a negative charge the field lines are directed inward, toward the charge
- The electric field is a vector and denoted by $\vec{E}$



Electric Field and Test Charge

- Consider a point in space where the electric field is $\vec{E}$
- If a charge q is placed at the point, the force is given by $\vec{F} = q\vec{E}$
  - The charge q is called a test charge
- By measuring the force on the test charge, the magnitude and direction of the electric field can be inferred



Electric Field, cont.

- The electric force is either parallel or antiparallel to the electric field
  - Parallel if q is positive and antiparallel if q is negative
- SI units of the electric field are N/C
- Coulomb's Law can be used to find the magnitude of the electric field, where Q is the charge producing the field and q is the test charge

$$F = \frac{kQq}{r^2} = qE$$

$$E = \frac{kQ}{r^2}$$

Electric Field, final

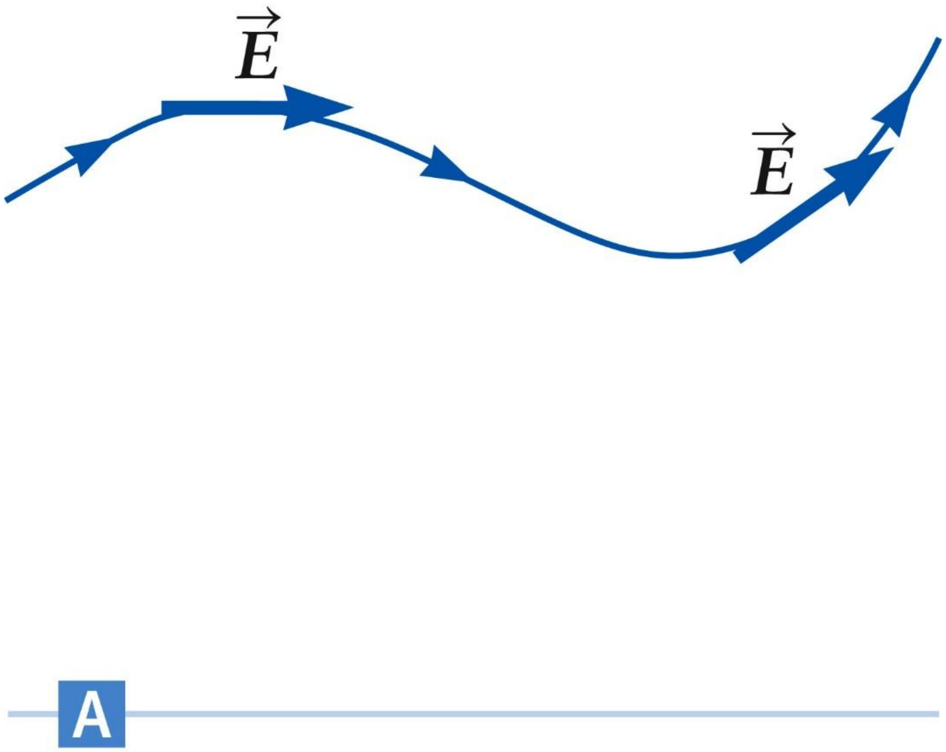
- The direction of the electric field is along the line connecting the charge producing the field to the point where the field is measured
- The electric field is directed away from Q when Q is positive
- The electric field is directed inward toward Q when Q is negative

Importance of the Electric Field

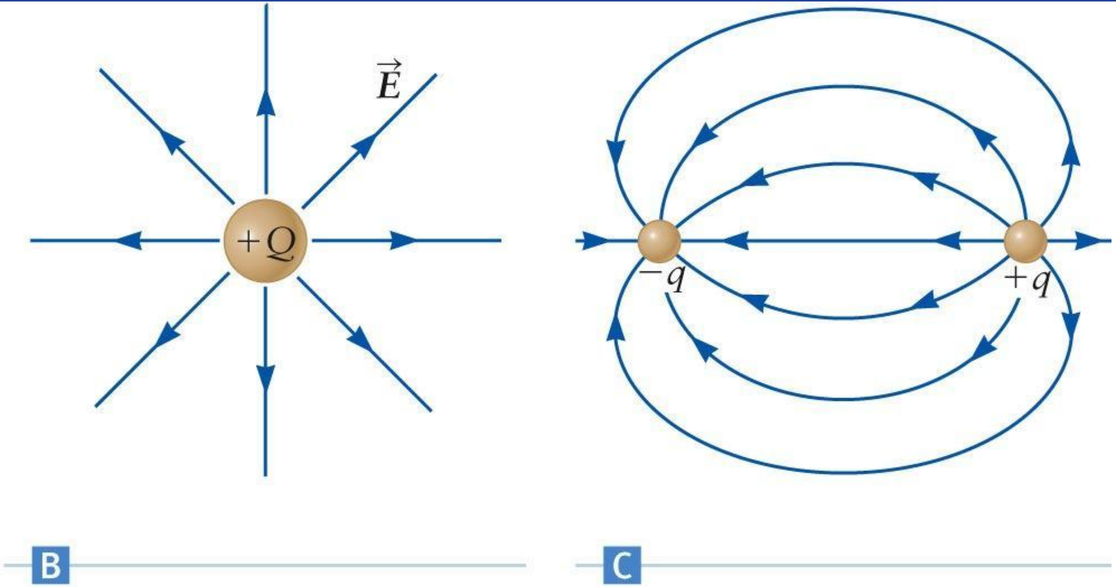
- An electric field is present even when there is no second (or test) charge present to experience the electric force
- Any charge or collection of charges will produce an electric field
- The electric field helps explain how the Coulomb force can act between two charges that are separated by large distances
- The electric field is essential for understanding electromagnetic waves

Drawing Electric Field Lines

- Another way to visualize an electric field is with electric field lines
- Field lines are a set of continuous lines that are always parallel to the electric field



Examples of Electric Field Lines



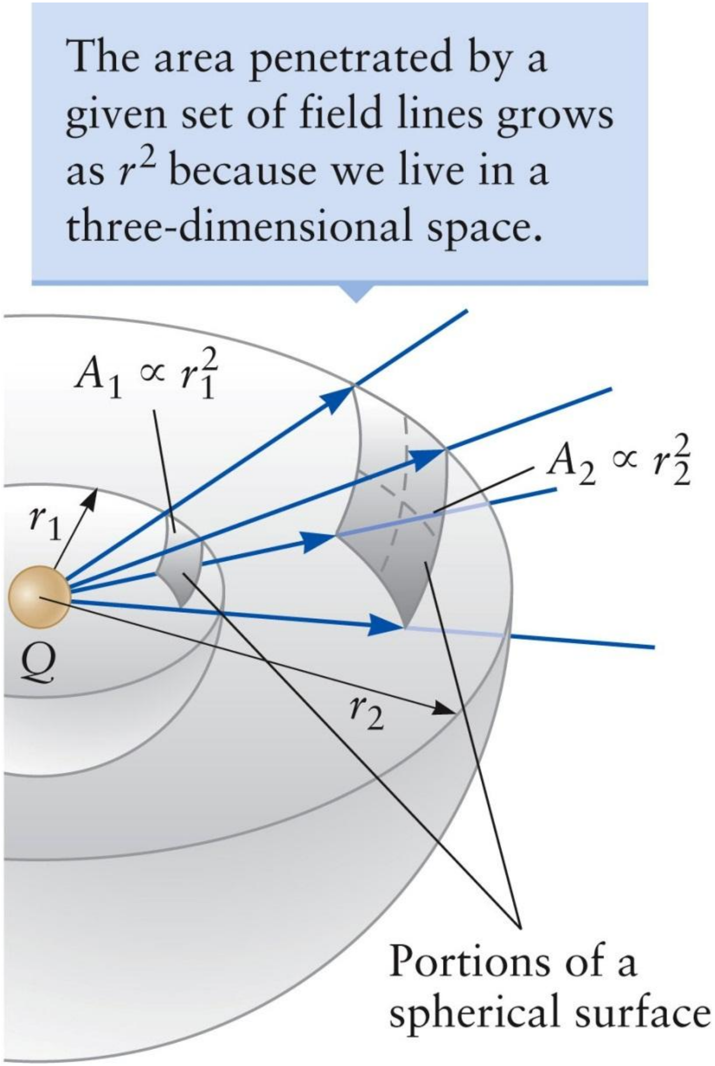
- The plot of the field lines does not show the magnitude of the field directly
- Changes in field strength can be inferred from the spacing of the field lines
  - The lines are most closely spaced where the field is the largest

Inverse Square Laws

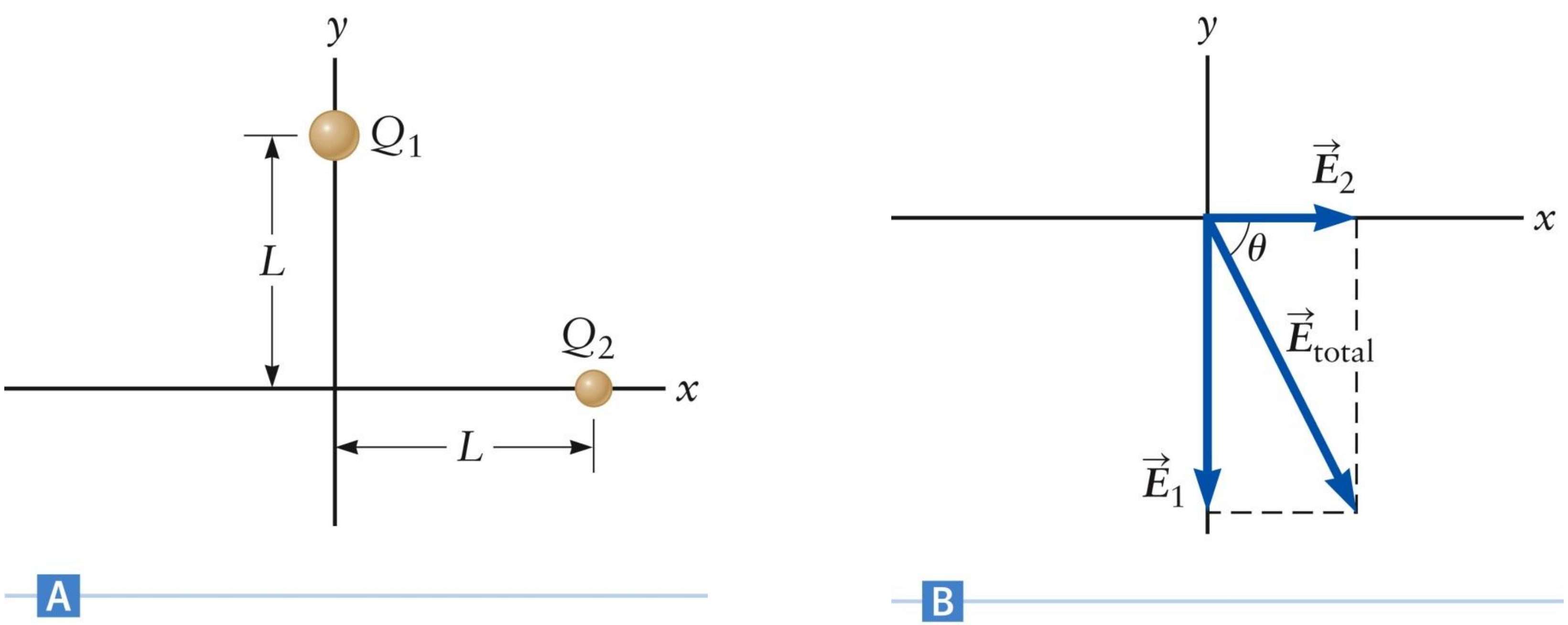
- The force between two point charges falls off as $1/r^2$
  - Where r is the separation between the charges
- The electric field also falls off as $1/r^2$
  - The electric force also obeys an inverse square law
- The charged particle "sets up" field lines in its neighborhood
  - The density of the field lines is proportional to the amount of charge on the particle
- The electric field produces a force on a nearby test charge and on any other nearby charges
  - The magnitude of the force is proportional to the density of field lines at the test charge

Inverse Square Laws, cont.

- The electric field lines emanate outward from a point charge
- They intercept larger and larger surface areas
- The surfaces are spherical
  - Their areas increase as $A \propto r^2$
  - The number of field lines per unit area falls as $1/r^2$



Electric Fields and Multiple Charges



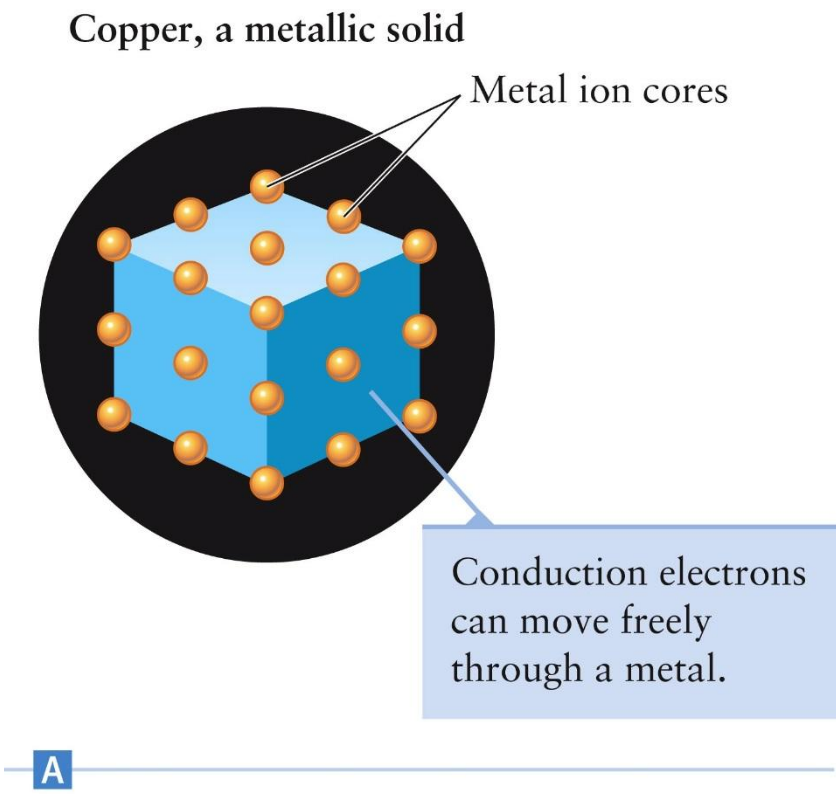
- To find the electric field due to multiple charges use the principle of superposition
  - Find the electric fields due to each charge
  - Add them as vectors

Drawing Electric Field Lines

- Field lines must always begin on positive charges
- Field lines must always end on negative charges
- Electric fields also obey the superposition principle
  - When adding the fields from multiple charges, always add them as vectors

Conductors

- Each atom by itself is electrically neutral
  - Equal numbers of protons and electrons
  - This example is copper
- When these atoms come together to form the piece of metal electrons are freed



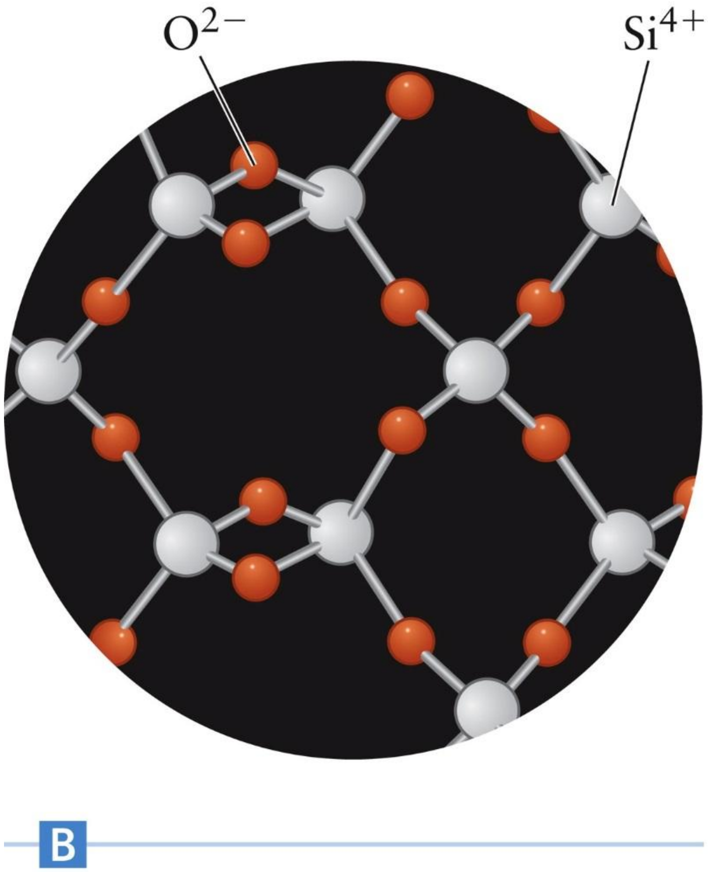
Conductors, cont.

- These electrons move freely through the entire piece of metal
- These electrons are called ***conduction electrons***
- The electrons leave behind positively charged ion cores that are bound and not mobile
- A piece of metal can also accept extra electrons or release some of its conduction electrons so the entire object can acquire a net positive or negative charge

Insulators

- In ***insulators*** the electrons are not able to move freely through the material
- Examples include quartz, plastic and amber
- This example is quartz (SiO_2)

Quartz, an insulator



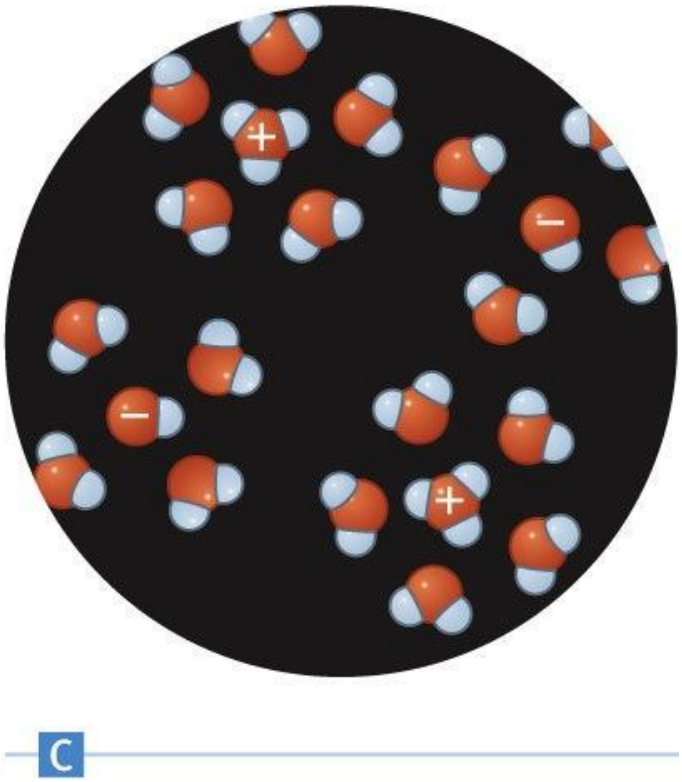
Insulators, cont.

- Electrons cannot escape from these ions
- There are no conduction electrons available to carry charge through the solid
- If extra electrons are placed on an insulator, they tend to stay in the place where initially placed

Liquids and Gases

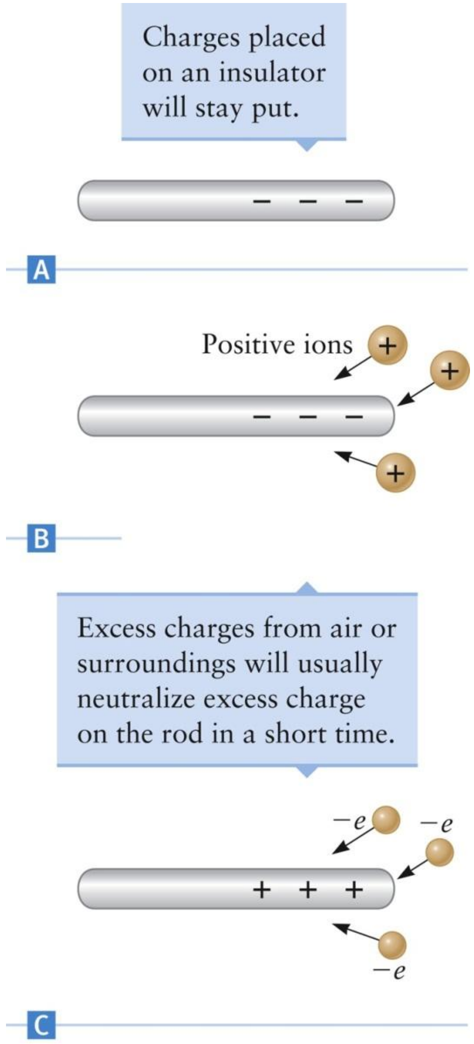
- The total charge is zero and the sample is neutral
- A few molecules always dissociate into free ions
- These ions can carry charge from place to place similarly to the conduction electrons
- This example is water, but gases are similar

Water, a liquid



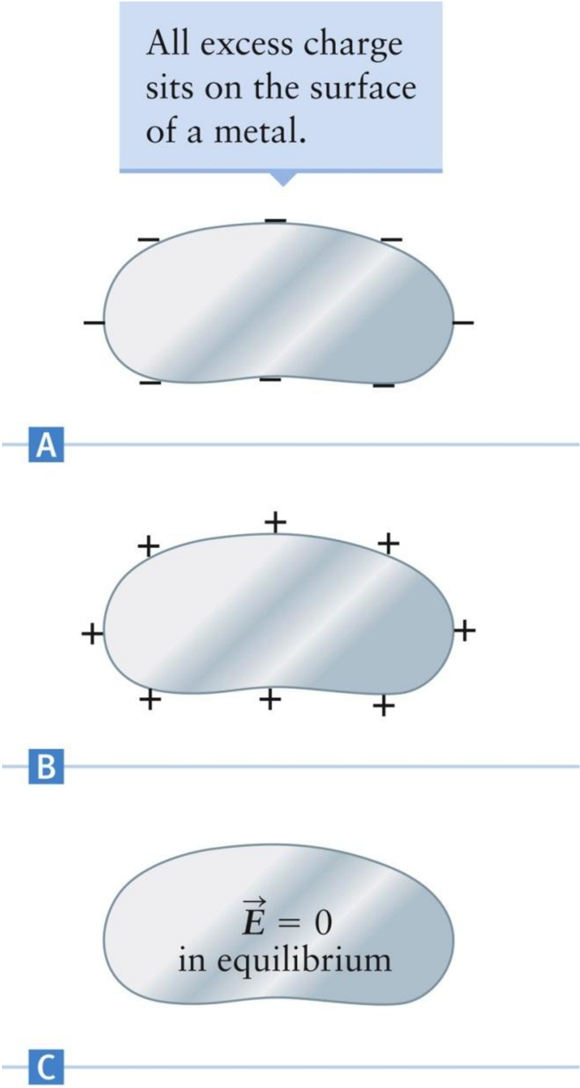
Charging an Insulator

- A few electrons are placed on the insulator
- They will tend to stay where they are placed
- The insulator will eventually be neutralized
  - The excess electrons will attract free ions from the air
  - They will neutralize the original charge



Excess Charge on a Metal

- Electrons can move easily through a metal
- Excess electrons will be distributed on the surface of the metal
- Eventually, all the charge carriers will come to rest and be in static equilibrium



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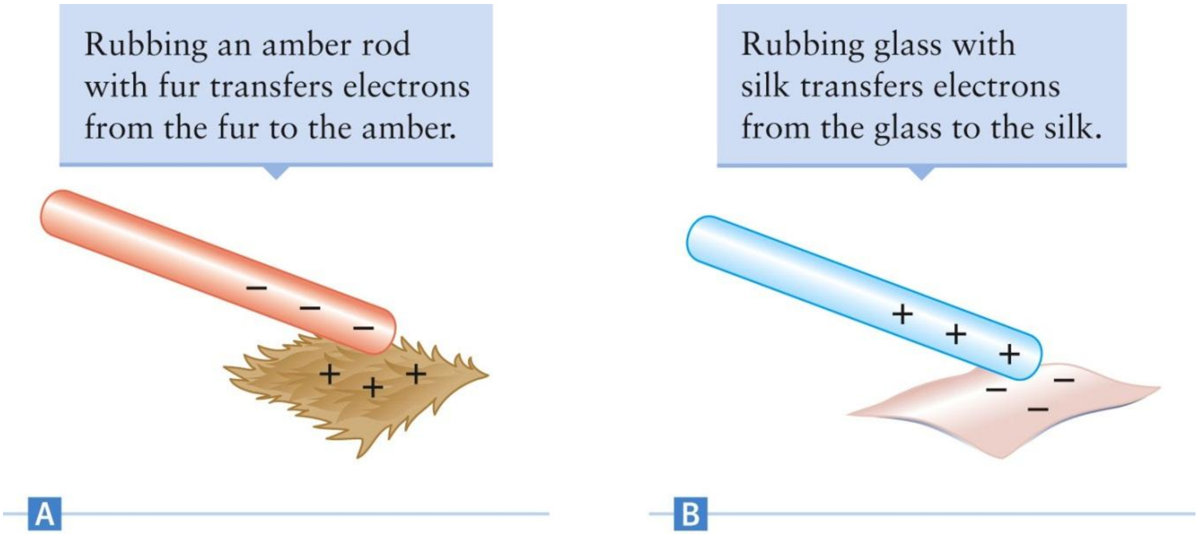
Metals, cont.

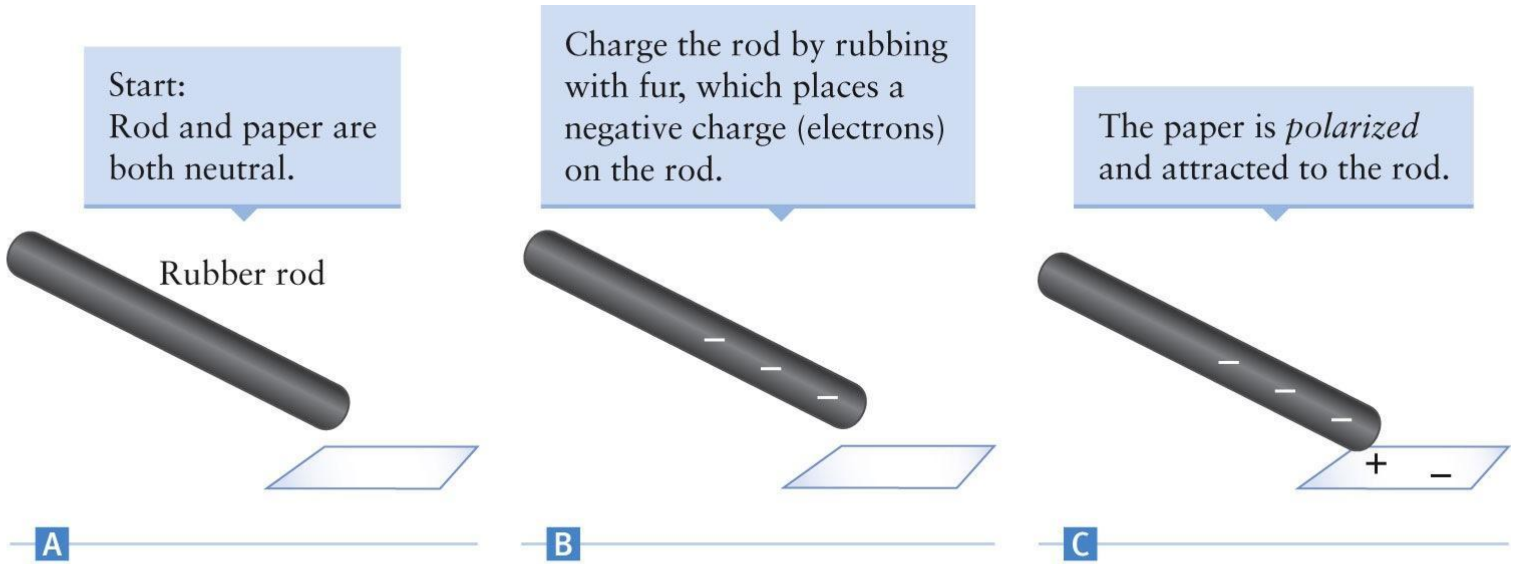
- For a metal in equilibrium
  - Any excess electrons must be at the surface
  - The electric field is zero inside a metal in equilibrium
- The net charge could also be positive
  - Electrons would have been removed from the metal
  - The deficit of electrons will be at the surface, so the surface will have a net positive charge
    - This does not correspond to placing positive ions on the metal

Charging an Object by Rubbing



- The act of rubbing causes some charge to be transferred from one material to another
  - Example: when rubbing amber with fur, electrons are moved from the fur to the amber
  - The amber acquires a net negative charge
  - The fur is left with a net positive charge
- Applies to many combinations of materials

Polarization

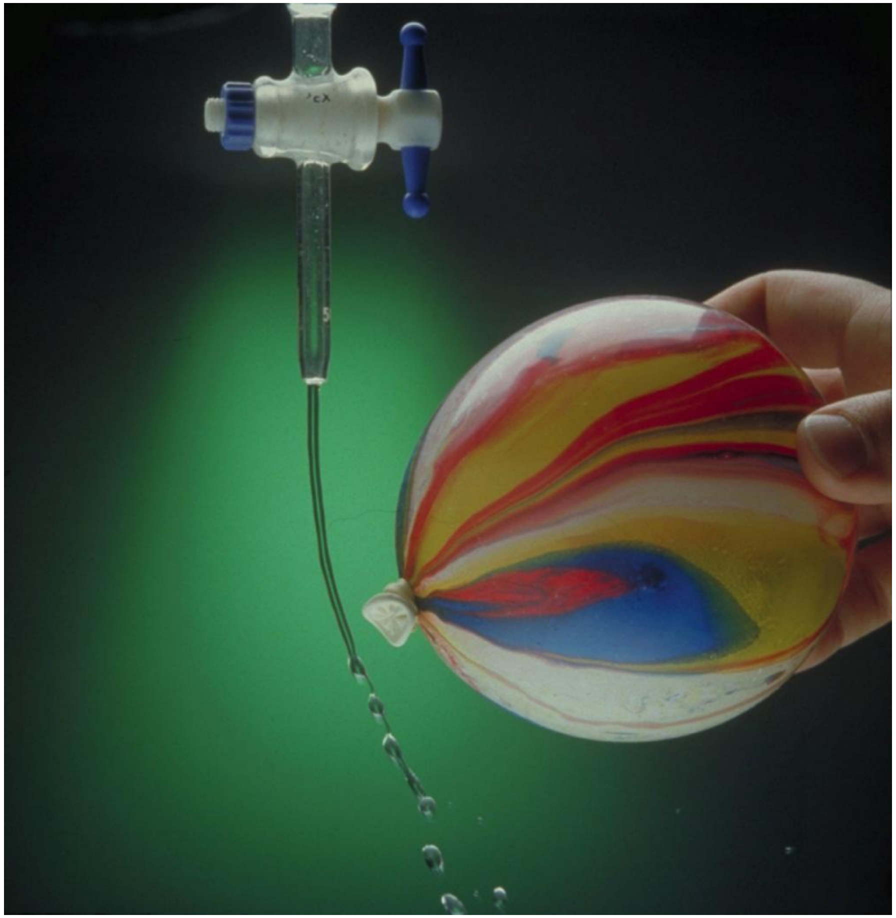


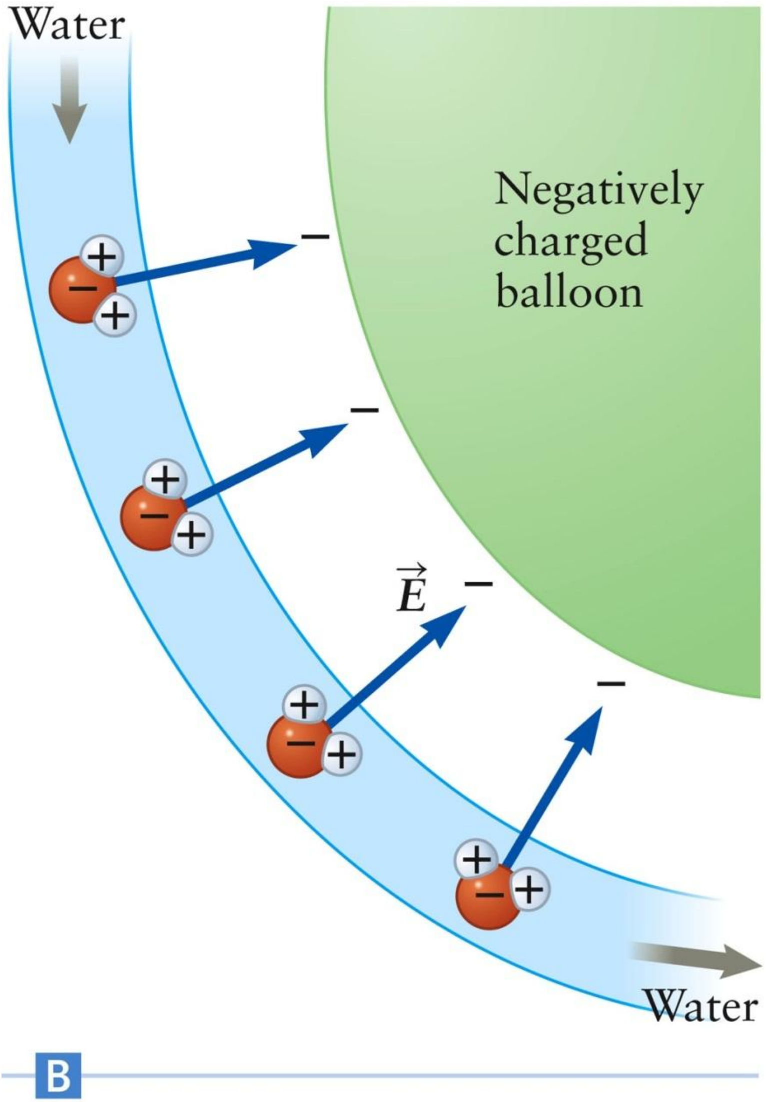
- The rod and paper are both neutral
- The rod is rubbed by the fur, obtaining a negative charge
- The presence of the rod causes the electrons in the paper to be repelled and the positive ions are attracted
- The paper is said to be ***polarized***

Polarization, cont.

- The paper is still electrically neutral
- The negative side of the paper is repelled
- The positive side of the paper is closer to the rod so it will experience a greater electric force
- The net effect is that the positive side of the paper is attracted to the negative rod
- There can be an electric force on an object even when the object is electrically neutral, provided the object is polarized

Polarization, Balloon and Water Example





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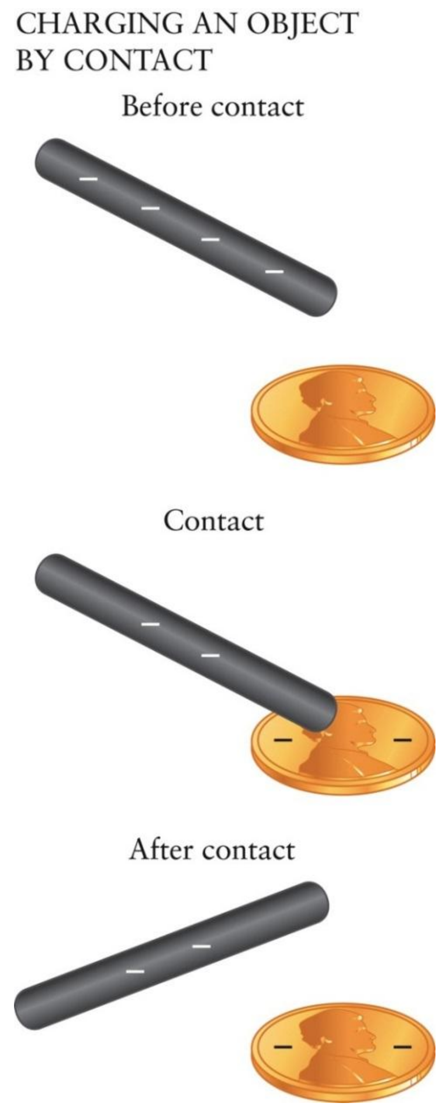
Electrical "Ground"

- The idea of *electrical ground* plays an important role in many situations
- If you watch the excess electrons on a charged rod you would see them eventually flow to the ground
- The ground is generally moist, so it conducts well
- Because the ground is everywhere, it provides a common path that excess charge can use to flow from one spot to another
- The term *ground* is used to denote a path or destination of the excess charges, even if dirt is not actually involved

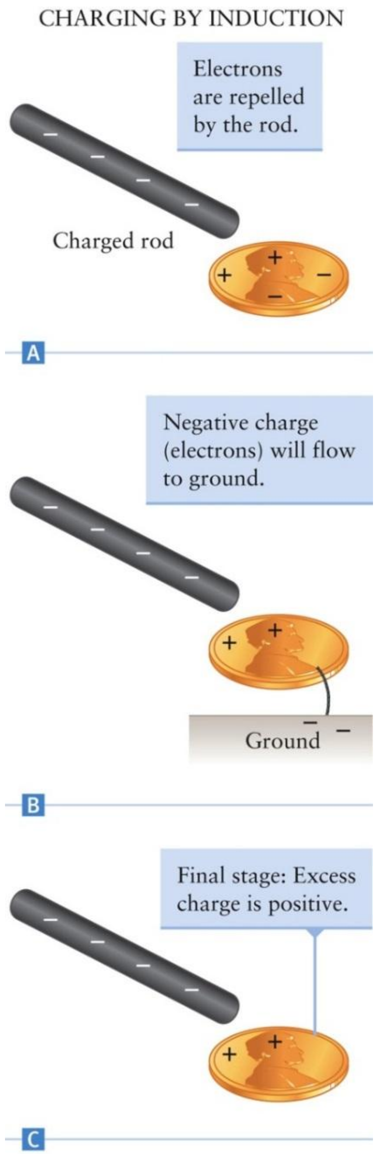
Charging by Contact

- Assume a negatively charged rubber rod
- Bring the rod into contact with the metal
- Some of the excess electrons will move to the metal
- The metal has been charged by contact



Charging by Induction

- Charging by induction makes use of polarization
- The negatively charged rod is first brought near the metal, polarizing the metal
- A connection is made from the piece of metal to electrical ground using a wire



Charging by Induction, cont.

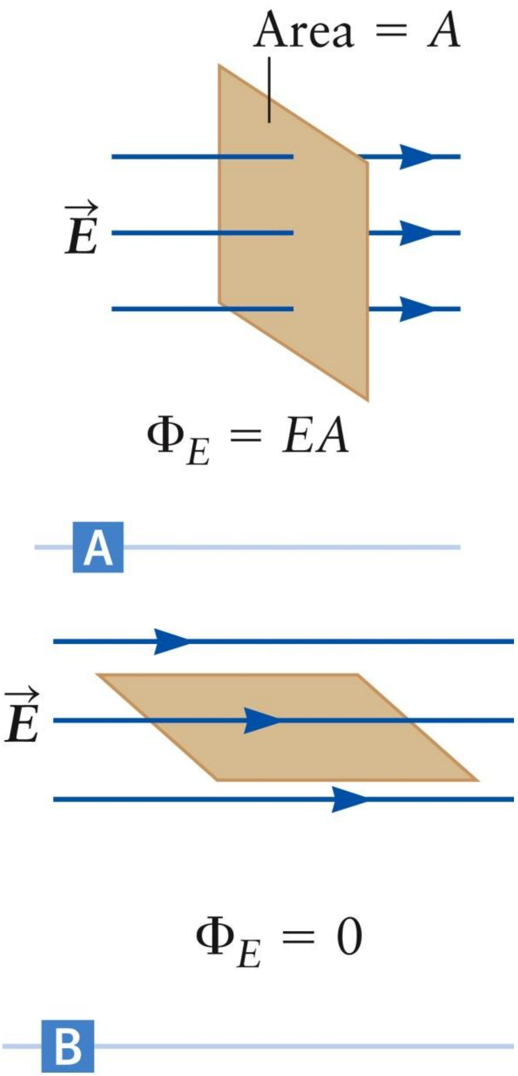
- The electrons are able to use the wire to move even farther from the charged rod
- Some of the electrons will move off the original piece of metal and into the electrical ground region
- The final step is to remove the grounding wire
- The original piece of metal will be left with a net positive charge
  - The positive charge is produced by removing electrons

Electric Flux and Gauss' Law

- Gauss' Law can be used to find the electric field of a complex charge distribution
  - Easier than treating it as a collection of point charge and using superposition
- To use Gauss' Law, a quantity called ***electric flux*** is needed
- The electric flux is equal the product of the electric field that passes through a particular surface and the area of the surface
  - The electric flux is denoted by Φ_E

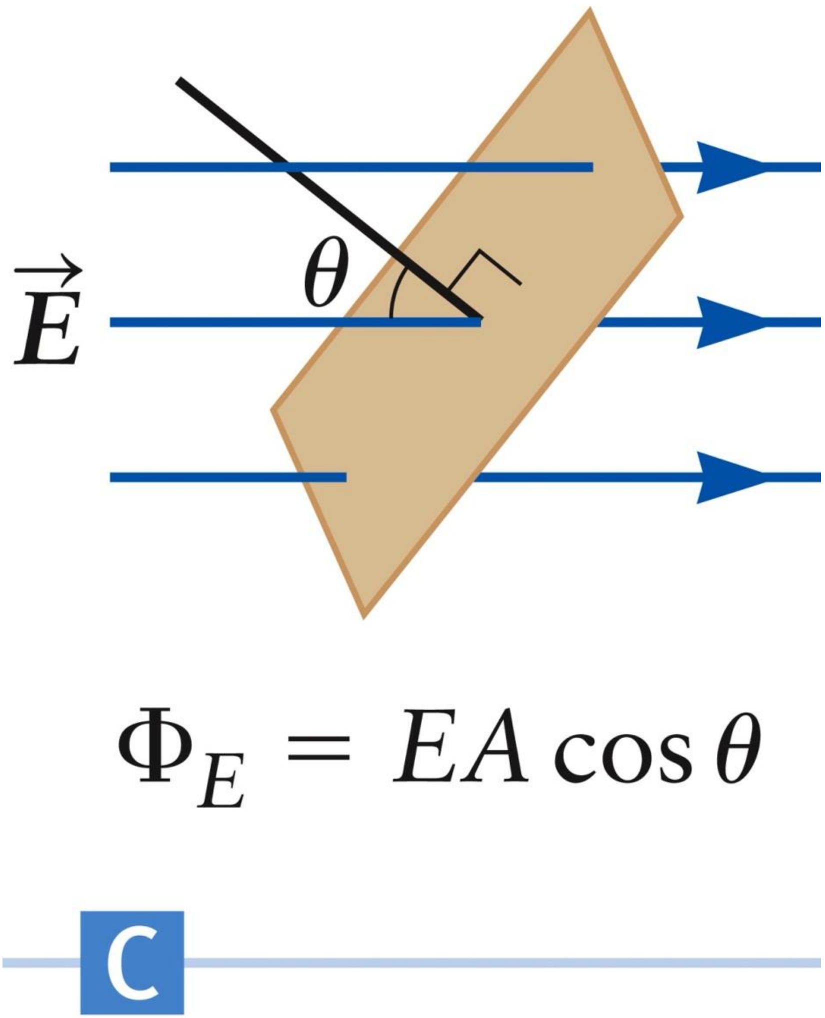
Electric Flux Examples

- Fig. A
  - The electric field is perpendicular to the surface of area A
  - $\Phi_E = E A$
- Fig. B
  - The electric field is parallel to the surface of area A
  - $\Phi_E = 0$
  - No field lines pass through the area



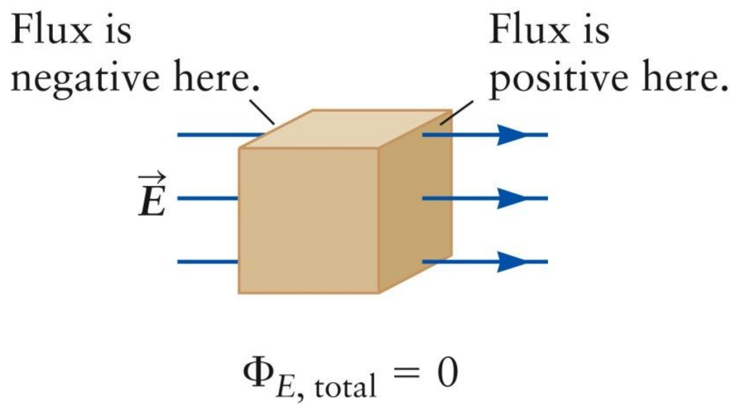
Electric Flux Examples, cont.

- Fig. C
  - The electric field makes an angle with the surface
  - $\Phi_E = E\,A \cos\theta$
- Flux is a scalar quantity



Electric Flux Examples, Closed Surface

- The flux is positive if the field is directed out of the region surrounded by the surface and negative if going into the region
- Fig. D and E
  - The total flux is the sum of the contributions of the fields going in and coming out
  - $\Phi_E = 0$



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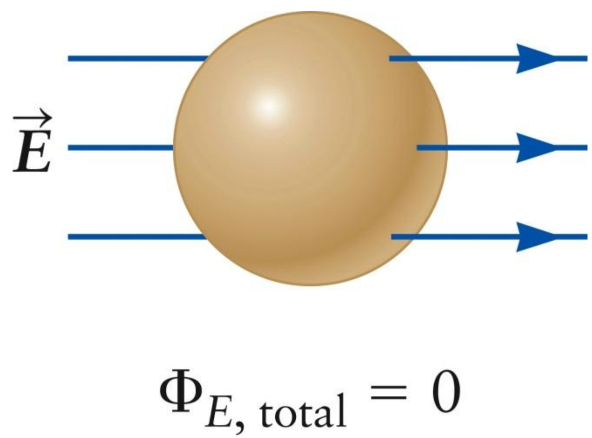

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Gauss' Law

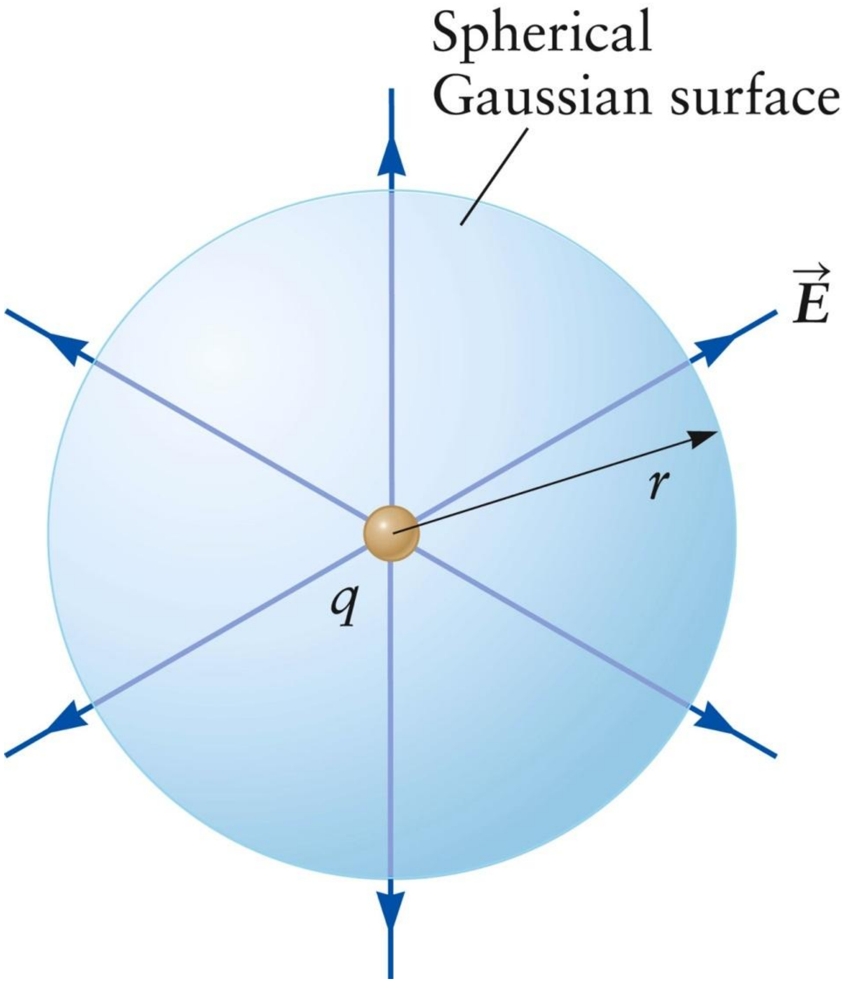
- Gauss' Law says that the electric flux through any closed surface is proportional to the charge *q* inside the surface

$$\Phi_E = \frac{q}{\varepsilon_o}$$

- The constant ε_o is the permittivity of free space
  - This was encountered in one form of Coulomb's Law
- Since the flux depends on the electric field, Gauss' Law can be used to find the field

Gauss' Law: Point Charge

- Choose a ***Gaussian surface***
  - Want a surface that will make the calculation as easy as possible
  - Choose a surface that matches the symmetry of the problem
- For a point charge, the field lines have a spherical symmetry



Gauss' Law: Point Charge, cont.

- The spherical symmetry means that the magnitude of the electric field depends only on the distance from the charge
- The electric field is directed radially
  - Either inward or outward
- A surface that matches this symmetry is a sphere centered on the charge
- Because of the symmetry, the magnitude of the field is the same at all points on the sphere
- The field is perpendicular to the sphere at all points where it intersects the surface

Gauss' Law: Point Charge, final

- Since the field is perpendicular to the area, the flux is the product of the field and the area: $\Phi_E = E\, A_{sphere}$
- A_{sphere} is the area of the Gaussian sphere
- With a radius of r, $A_{sphere} = 4\, \pi\, r^2$
- Therefore, $\Phi_E = 4\, \pi\, r^2\, E$
- From Gauss' Law,

$$\Phi_E = 4\pi r^2 E = \frac{q}{\varepsilon_o} \quad and \quad E = \frac{q}{4\pi\varepsilon_o r^2}$$

- This agrees with the result from Coulomb's Law

Problem Solving Strategy

- ***Recognize the principle***
  - Calculate the electric flux through a Gaussian surface
  - The choice of the Gaussian surface is key!
- ***Sketch the problem***
  - Draw the charge distribution
  - Use the symmetry of the distribution to sketch the electric field
  - The Gaussian surface should match the symmetry of the electric field

Problem Solving Strategy, cont.

- ***Identify the relationships***
  - Your Gaussian surface should satisfy one or more of the following conditions:
    - The field has constant magnitude over all or much of the surface and makes a constant angle with the surface
      - The most convenient surface is one that is perpendicular to the field at all (or most) points
    - The field may be zero over a portion of the surface
      - The flux through that part of the surface is zero
    - The field may be parallel to some part of the surface
      - The flux through that part of the surface is zero

Problem Solving Strategy, final

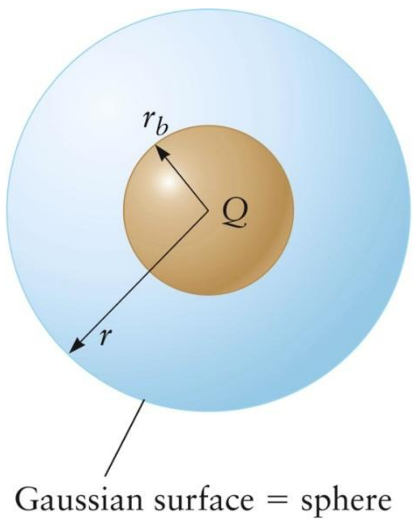
- ***Solve***
  - Calculate the total electric flux through the entire Gaussian surface
  - Find the total electric charge inside the surface
  - Apply Gauss' Law to solve for the electric field
- ***Check***
  - Consider what your answer means
  - Check that your answer makes sense

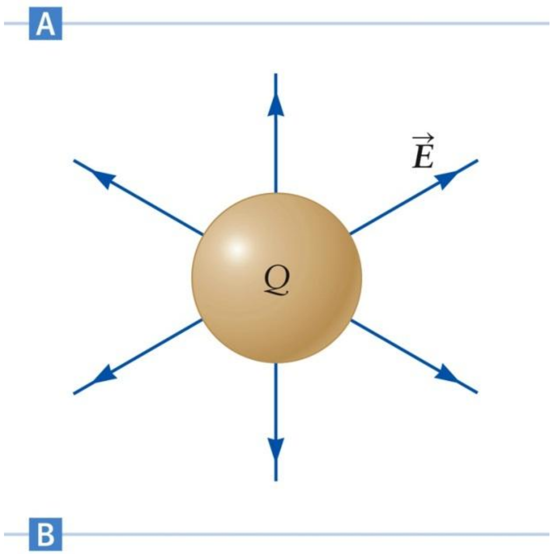
Electric Field from Spherical Charge

- Given a uniform spherical ball of charge
- Choose a sphere as a Gaussian surface

$$E = \frac{Q}{4\pi\varepsilon_o r^2} = \frac{kQ}{r^2}$$

- The electric field from any spherical distribution of charge is the same as the field from a point charge with the same total charge
- This applies only outside the ball of charge

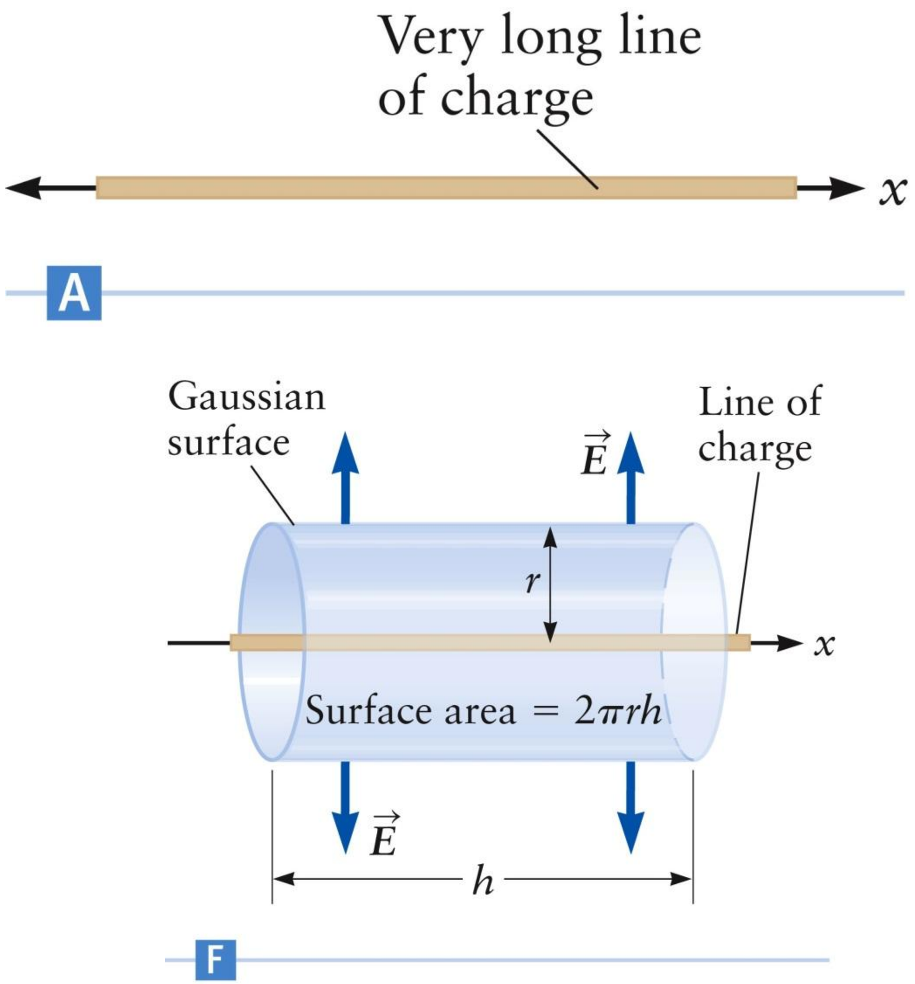




Electric Field from Line of Charge

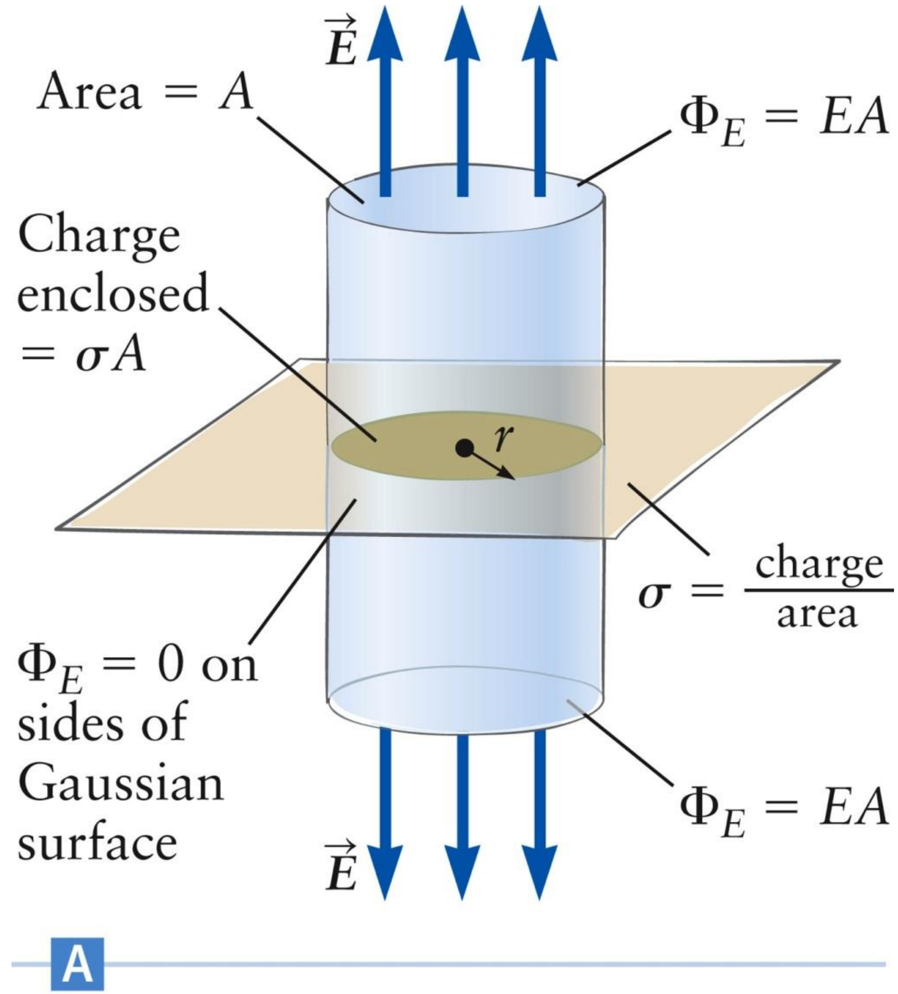
- The line of charge has a total length L and a total charge Q
- The electric field is perpendicular to the line
- Choose a cylinder of radius r for the Gaussian surface

$$E = \frac{Q}{4\pi\varepsilon_o L r}$$



Electric Field: Flat Sheet of Charge

- The large, flat sheet of charge has a charge per unit area of σ
- Choose a cylinder as the Gaussian surface
- The field through the sides of the surface is zero
- Through each end of the surface, Φ_E = EA
- Since there are two ends, Φ_E = 2EA



DISCLAIMER: This document is a draft and the information contained herein is subject to change as this document is currently undergoing review. The final version of this teacher's resource manual will be published as soon as the review has been completed.

Flat Sheet of Charge, cont.

- The total charge is equal to the charge / area multiplied by the cross-sectional area of the cylinder
  - $q = \sigma A$
- Therefore, the electric field is

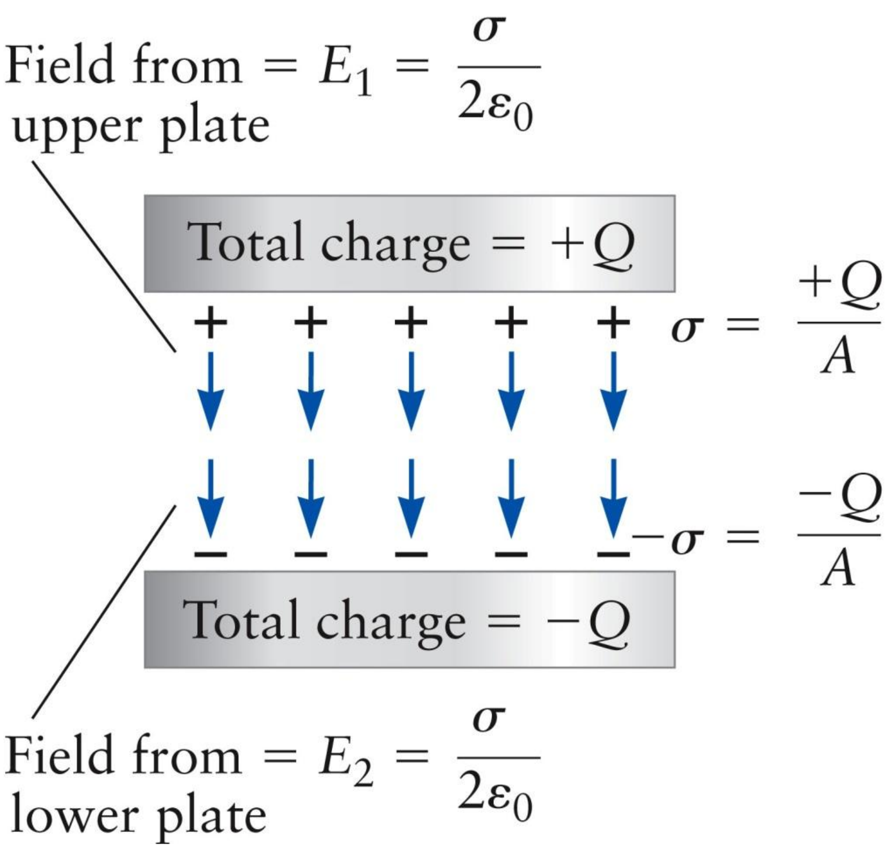
$$2EA = \frac{\sigma A}{\varepsilon_o}$$

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

- The electric field is constant and independent of the distance from the sheet of charge

Capacitor

- A capacitor consists of two parallel metal plates that carry charges of +Q and –Q
- The excess charge on the two plates will attract each other and draw all the excess charge to the inner sides of the two plates



Capacitor, cont.

- Each plate has an area *A* and charge densities of $+\sigma = +Q/A$ and $-\sigma = -Q/A$
- The total field is the vector sum of the fields from the individual plates
  - From superposition
- The field between the plates is

$$E = \frac{\sigma}{\varepsilon_o} = \frac{Q}{\varepsilon_o A}$$

Notes on Gaussian Surfaces

- To make analysis easier, some simplifications have been made in the examples
  - Highly symmetric charge distributions
  - Gaussian surfaces on which the electric field was either constant or zero
- Gauss' Law applies to any surface and any charge distribution
  - Even with little or no symmetry
- The total electric flux through a closed surface depends only on the total charge enclosed