18.1 The Origin of Electricity

The electrical nature of matter is inherent in atomic structure.

\[ m_p = 1.673 \times 10^{-27} \text{ kg} \]
\[ m_n = 1.675 \times 10^{-27} \text{ kg} \]
\[ m_e = 9.11 \times 10^{-31} \text{ kg} \]
\[ e = 1.60 \times 10^{-19} \text{ C} \]

In nature, atoms are normally found with equal numbers of protons and electrons, so they are electrically neutral.

By adding or removing electrons from matter it will acquire a net electric charge with magnitude equal to \( e \) times the number of electrons added or removed, \( N \).

\[ q = Ne \]

**Example 1 A Lot of Electrons**

How many electrons are there in one coulomb of negative charge?

\[ N = \frac{q}{e} = \frac{1.00 \text{ C}}{1.60 \times 10^{-19} \text{ C}} = 6.25 \times 10^{18} \]
It is possible to transfer electric charge from one object to another.

The body that loses electrons has an excess of positive charge, while the body that gains electrons has an excess of negative charge.

**LAW OF CONSERVATION OF ELECTRIC CHARGE**

During any process, the net electric charge of an isolated system remains constant (is conserved).

*Like charges repel and unlike charges attract each other.*
Not only can electric charge exist on an object, but it can also move through an object.

Substances that readily conduct electric charge are called electrical conductors.

Materials that conduct electric charge poorly are called electrical insulators.

Charging by contact.

Charging by induction.

The negatively charged rod induces a slight positive surface charge on the plastic.
COULOMB’S LAW

The magnitude of the electrostatic force exerted by one point charge on another point charge is directly proportional to the magnitude of the charges and inversely proportional to the square of the distance between them.

\[ F = k \frac{|q_1 q_2|}{r^2} \]

where:
- \( F \) is the force of attraction or repulsion between the charges
- \( k \) is Coulomb’s constant
- \( |q_1 q_2| \) is the product of the magnitudes of the charges
- \( r \) is the distance between the charges

\( k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2 \)

\( \varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}) \)

Example 3: A Model of the Hydrogen Atom

In the Bohr model of the hydrogen atom, the electron is in orbit about the nuclear proton at a radius of \( 5.29 \times 10^{-11} \text{m} \). Determine the speed of the electron, assuming the orbit to be circular.

\[ F = \frac{k |q_1 q_2|}{r^2} = \frac{(8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2)(1.60 \times 10^{-19} \text{ C})^2}{(5.29 \times 10^{-11} \text{m})^2} = 8.22 \times 10^{-8} \text{ N} \]

Using \( F = ma_e = mv^2/r \)

\[ v = \sqrt{Fr/m} = \sqrt{\frac{[8.22 \times 10^{-8} \text{N}] [5.29 \times 10^{-11} \text{m}]}{9.11 \times 10^{-31} \text{kg}}} = 2.18 \times 10^6 \text{ m/s} \]
Example 4 Three Charges on a Line

Determine the magnitude and direction of the net force on \( q_1 \).

\[
F_{12} = k \frac{|q_1| |q_2|}{r_{12}^2} = \frac{8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2}{(0.20 \text{ m})^2} \times 3.0 \times 10^{-4} \text{ C} \times 4.0 \times 10^{-4} \text{ C} = 2.7 \text{ N}
\]

\[
F_{13} = k \frac{|q_1| |q_3|}{r_{13}^2} = \frac{8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2}{(0.15 \text{ m})^2} \times 7.0 \times 10^{-4} \text{ C} \times 4.0 \times 10^{-4} \text{ C} = 8.4 \text{ N}
\]

\[
\vec{F} = \vec{F}_{12} + \vec{F}_{13} = -2.7 \text{ N} + 8.4 \text{ N} = +5.7 \text{ N}
\]

18.6 The Electric Field

The positive charge experiences a force which is the vector sum of the forces exerted by the charges on the rod and the two spheres.

This test charge should have a small magnitude so it doesn't affect the other charge.
**Example 6** A Test Charge

The positive test charge has a magnitude of 3.0 \times 10^{-8} \text{C} and experiences a force of 6.0 \times 10^{-8} \text{N}.

(a) Find the force per coulomb that the test charge experiences.

(b) Predict the force that a charge of +12 \times 10^{-8} \text{C} would experience if it replaced the test charge.

\[
\frac{F}{q_o} = \frac{6.0 \times 10^{-8} \text{N}}{3.0 \times 10^{-8} \text{C}} = 2.0 \text{ N/C}
\]

\[
F = (2.0 \text{ N/C})(12.0 \times 10^{-8} \text{C}) = 24 \times 10^{-8} \text{N}
\]

**Example 7** An Electric Field Leads to a Force

The charges on the two metal spheres and the ebonite rod create an electric field at the spot indicated. The field has a magnitude of 2.0 N/C. Determine the force on the charges in (a) and (b).

It is the surrounding charges that create the electric field at a given point.
(a) \[ F = \left| q_o \right| E = (2.0 \text{ N/C}) (18.0 \times 10^{-9} \text{ C}) = 36 \times 10^{-8} \text{ N} \]

(b) \[ F = \left| q_o \right| E = (2.0 \text{ N/C}) (24.0 \times 10^{-9} \text{ C}) = 48 \times 10^{-8} \text{ N} \]

**Example 10 The Electric Field of a Point Charge**

The isolated point charge of \( q = +15 \mu\text{C} \) is in a vacuum. The test charge is 0.20m to the right and has a charge \( q_o = +15 \mu\text{C} \).

Determine the electric field at point P.

\[ \vec{E} = \frac{\vec{F}}{q_o} \]

\[ F = k \frac{|q_o| |q|}{r^2} \]

\[ E = F \frac{|q|}{|q_o|} = \frac{2.7 \text{ N}}{0.80 \times 10^{-8} \text{ C}} = 3.4 \times 10^6 \text{ N/C} \]
The Electric Field

\[ E = \frac{F}{|q_o|} = k \frac{|q|}{r^2} \frac{1}{|q_o|} \]

The electric field does not depend on the test charge.

Point charge \( q \):

\[ E = k \frac{|q|}{r^2} \]

Example 11 The Electric Fields from Separate Charges May Cancel

Two positive point charges, \( q_1 = +16 \mu C \) and \( q_2 = +4.0 \mu C \) are separated in a vacuum by a distance of 3.0m. Find the spot on the line between the charges where the net electric field is zero.

Conceptual Example 12 Symmetry and the Electric Field

Point charges are fixes to the corners of a rectangle in two different ways. The charges have the same magnitudes but different signs.

Consider the net electric field at the center of the rectangle in each case. Which field is stronger?

\[ E = k \frac{|q|}{r^2} \]

\[ E_1 = E_2 \]

\[ k \left( 16 \times 10^{-6} \text{C} \right) = k \left( 4.0 \times 10^{-6} \text{C} \right) \]

\[ \frac{1}{d^2} = \frac{1}{(3.0m - d)^2} \]

\[ 2.0(3.0m - d)^2 = d^2 \]

\[ d = +2.0 \text{ m} \]
\[ E = \frac{q}{\varepsilon_o A} = \frac{\sigma}{\varepsilon_o} \]

\[ \varepsilon_o = 8.85 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2) \]

Electric field lines or lines of force provide a map of the electric field in the space surrounding electric charges.

Electric field lines are always directed away from positive charges and toward negative charges.

Electric field lines always begin on a positive charge and end on a negative charge and do not stop in midspace.
The number of lines leaving a positive charge or entering a negative charge is proportional to the magnitude of the charge.

**Conceptual Example 13 Drawing Electric Field Lines**

There are three things wrong with part (a) of the drawing. What are they?

At equilibrium under electrostatic conditions, any excess charge resides on the surface of a conductor.

At equilibrium under electrostatic conditions, the electric field is zero at any point within a conducting material.

The conductor shields any charge within it from electric fields created outside the conductor.
The Electric Field Inside a Conductor: Shielding

The electric field just outside the surface of a conductor is perpendicular to the surface at equilibrium under electrostatic conditions.

Conceptual Example 14 A Conductor in an Electric Field

A charge is suspended at the center of a hollow, electrically neutral, spherical conductor. Show that this charge induces

(a) a charge of \(-q\) on the interior surface and
(b) a charge of \(+q\) on the exterior surface of the conductor.

Gauss' Law

\[ E = \frac{kq}{r^2} = \frac{q}{(4\pi\varepsilon_0 r^2)} \]

\[ E = \frac{q}{(A\varepsilon_0)} \]

\[ EA = \frac{q}{\varepsilon_0} \]

Electric flux, \(\Phi_E = EA\)

\[ \Phi_E = \sum (E \cos \phi) \Delta A \]
**18.9 Gauss' Law**

**GAUSS' LAW**

The electric flux through a Gaussian surface is equal to the net charge enclosed in that surface divided by the permittivity of free space:

$$\Phi_E = \sum (E \cos \phi) \Delta A = \frac{Q}{\varepsilon_0}$$

*SI Units of Electric Flux: N·m²/C*

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**Example 15 The Electric Field of a Charged Thin Spherical Shell**

A positive charge is spread uniformly over the shell. Find the magnitude of the electric field at any point (a) outside the shell and (b) inside the shell.

$$\sum (E \cos \phi) \Delta A = \frac{Q}{\varepsilon_0}$$

(a) Outside the shell, the Gaussian surface encloses all of the charge.

$$E(4\pi r^2) = \frac{Q}{\varepsilon_0}$$

(b) Inside the shell, the Gaussian surface encloses no charge.

$$E = 0$$
18.9 Gauss' Law

18.10 Copiers and Computer Printers

Paths of scanning laser beam

Xerographic drum

Copiers and Computer Printers

18.10 Copiers and Computer Printers