Physics 1214 — Chapter 17: Electric Charge and Electric Field — 01/14

Introduction

electrostatic interactions

- interactions between ***electric charges***
- at rest in our frame of reference
- modeled by Coulomb's equation
- described by an ***electric field***

1 Electric Charge

electric charge

> We cannot say what electric charge is; we can only describe its properties and its behavior.

- two kinds named positive and negative
- one of the fundamental attributes of the particles of which matter is made
- the interaction of electric charges are responsible for the structure and properties of atoms and molecules (refer to periodic table)

> Two positive charges or two negative charges repel each other; a positive and a negative charge attract each other.

The structure of ordinary matter can be described in terms of three particles: ***electrons***, ***protons***, and ***neutrons***.

- ***electron***:
  - negatively charged
  - fundamental
  - mass = $m_e = 9.1093826(16) \times 10^{-31}$ kg
- ***proton***:
  - positively charged
  - mass = $m_p = 1.67262171(29) \times 10^{-27}$ kg
- ***neutron***:
  - neutral or uncharged
  - mass = $m_n = 1.67492728(29) \times 10^{-27}$ kg

nucleus: dense core of the atom; consists of ***neutrons*** and ***protons***
atomic number: the number of protons or electrons in neutral atoms of any element
negative ion: a negatively charged atom to which an electron has been added
positive ion: a positively charged atom to which an electron has been removed
ionization: the gaining or adding of electrons
ion: an atom that has lost or gained one or more electrons

2 Conductors and Insulators

conductor: materials that permit charge to move through them; most metals are good conductors
insulator: materials that do not permit charge to move through them; most nonmetals are insulators
semiconductor: materials with properties that fall between good conductors and good insulators
induction: a process by which an object can give a charge to another object without losing any of its own charge
induced charges: excess charges in a target object caused by induction from a charged object
sink: a generic term used in physics (mathematics and engineering) to describe a reservoir where charges (or other "fluid") flows away from the system being observed versus a "source" from which charges (or other "fluid") flows into the system.

> When excess charge is placed on a solid conductor and is at rest, the excess charge rests entirely on the surface of the conductor.

polarization: in an insulator, electric charges can shift when there is a charge nearby producing a net charge on one side of the object and the opposite charge on the other side; an induced charge in an insulator

3 Conservation and Quantization of Charge

Conservation of Charge

> The algebraic sum of all the electric charges in any closed system is constant. Charge can be transferred from one object to another, and that is the only way in which an object can acquire a net charge.

Quantization of Charge

> The magnitude of the charge of the electron or proton is a natural unit of charge.

4 Coulomb's Law

Coulomb's Law

The magnitude F of the force that each of two point charges q_1 and q_2 a distance r apart exerts on the other is directly proportional to the product of the charges $(q_1 q_2)$ and inversely proportional to the square of the distance between them (r^2). The relationship is expressed symbolically as

$$F = k\frac{|q_1 q_2|}{4\pi r^2}.$$

This relationship is **Coulomb's Law**.

The SI unit of electric charge is called one **coulomb** (1C)

The value of k in SI units

$$k = 8.987551789 \times 10^9 \mathrm{N \cdot m^2/C^2} \simeq 8.99 \times 10^9 \mathrm{N \cdot m^2/C^2}$$

also

$$k = \frac{1}{4\pi\epsilon_0}$$

where $\epsilon_0 = 8.854 \times 10^{-12} \mathrm{C^2/(N \cdot m^2)}$

This interaction force

- always acts along the line joining the charges
- obeys Newton's third law

The fundamental unit of charge is the magnitude of the charge of an electron or a proton, denoted by e. As of January 2013, according to NIST

$$e = 1.602176565(35) \times 10^{-19}\mathrm{C}$$

principle of superposition: when two charges exert forces simultaneously on a third charge, the total force acting on that charge is the vector sum of the fores that the two charges would exert individually

5 Electric Field and Electric Forces

Using the concept of an ***electric field***, $\vec{\mathbf{E}}$, we can describe the effect charged particles have on each other–"action at a distance".

test charge: a charged object, placed in the system to determine whether there is an electric field at a particular point.
vector field: a vector quantity associated with every point in a region of space, different at different points. In general, each component of $\vec{\mathbf{E}}$, at any point, depends on all the coordinates of the point.

To define $\vec{\mathbf{E}}$ at any point, we place a test charge q' at the point and measure the electric force $\vec{\mathbf{F}}'$ on it.

When a charged particle with charge q' at a point P is acted upon by an electric force $\vec{\mathbf{F}}'$, the electric field, $\vec{\mathbf{E}}$, at that point is defined as

$$\vec{\mathbf{E}} = \frac{\vec{\mathbf{F}}'}{q'}.$$

the test charge q' can be either positive or negative. If it is positive, the directions of $\vec{\mathbf{F}}$ and $\vec{\mathbf{E}}'$ are the same; if it is negative, they are opposite.
In SI units, the unit of electric field magnitude is 1 N/C.

$\vec{\mathbf{E}}$ is not a single vector quantity, but an infinite set of vector quantities–a ***vector field***

For those of you who are curious and feel like we've missed the effect of the test charge SEE NOTE on page 558 for more precise explanation of a point charge effect on a conductor!

In an electrostatic situation, the $\vec{\mathbf{E}}$ at every point *within* the material of a conductor must be zero.

6 Calculating Electric Fields

Principle of superposition

The total $\vec{\mathbf{F}}$ at any point due to two or more charges is the vector sum of the fields that would be produced at that point by the individual charges.

source point: denoted by S in the text, the origination of the electric field caused by many point charges

field point: denoted by P in the text, the point where we want to find the electric field

Using the ***superposition principle*** the ***total electric field***,

$$\vec{\mathbf{E}}_{total} = \vec{\mathbf{E}}_1 + \vec{\mathbf{E}}_2 + \vec{\mathbf{E}}_3 + ...$$

The magnitude E of the electric field $\vec{\mathbf{E}}$ at point P due to a point charge q at point S, a distance r from P, is given by

$$E = k\frac{|q|}{r^2}.$$

By definition, the electric field produced by a positive point charge always points *away from* it, but the electric field produced by a negative point charge points *toward* it.

7 Electric Field Lines

electric field lines: an imaginary line drawn through a region of space so that, at every point, it is tangent to the direction of the electric field vector at that point.

- at every point in space, the electric field vector, $\vec{\mathbf{E}}$, at that point is tangent to the electric field line through that point
- electric field lines are close together in regions where the magnitude of $\vec{\mathbf{E}}$ is large, farther apart where it is small
- field line point away from positive charges and toward negative charges
- field lines never intersect (only one field line can pass through each point of the field)

dipole: two equal charges, one positive and one negative

Note: Most field drawings are 2-D slices of 3-D fields.

> The direction of a field line at a given point determines the direction of the particle's *acceleration*, not its *velocity*.

8 Gauss's Law and Field Calculations

Gaussian surface: an imaginary closed surface surrounding a charge distribution
electric flux: *the flux of the electric field*; intuitively: the "flow" of the electric field magnitude, $\vec{\mathbf{E}}$, through an area, A, of the Gaussian surface denoted by

$$\Phi_E = EA.$$

Roughly, the number of field lines that pass through A. More generally, non-perpendicular

$$\Phi_E = EA\cos\phi$$

.

Gauss' law

> The total ***electric flux*** Φ_E coming out of any closed surface (that is, a surface enclosing a definite volume) is proportional to the total (net) electric charge $Q_{enclosed}$ inside the surface, according to the relation
>
> $$\sum E_\perp \Delta A = 4\pi k Q_{enclosed}.$$
>
> The sum on the left side of this equation represents the operations of dividing the enclosing surface into small elements of area ΔA, computing $E_\perp \Delta A$ for each one, and adding all these products.

9 Charges on Conductors

So far for *electrostatics*:

- in the electrostatic system, $\vec{\mathbf{E}}$ at every point within a conductor is zero
- the charge on a solid conductor is located entirely on its surface

Conductor with a cavity:

- if no charge in the cavity → the only charge is as if the conductor is solid and thus the charge is located entirely on its surface
- if there exists charge in the cavity (not touching the conductor) → there is the charge in the cavity plus any charge on the surface, $q + q'$

Faraday's ice-pail experiment: metal pail with a lid, an insulating stand, and a charged metal ball with insulating thread; if the ball hangs with the lid closed (not touching the pail), it induces a negative charge on the interior surface of the pail and a positive charge on the exterior surface; once the ball touches the pail, the ball becomes part of the pail and the ball loses its charge to the pail

Faraday cage: in a uniform electric field a conductive closed surface surrounding a volume redistributes charge on its surface such that the interior of the volume has a total electric field of zero (Gauss' law); also knowing as *electrostatic shielding*.