3.10: Summary

Key Terms

charging by induction	process by which an electrically charged object brought near a neutral object creates a charge separation in that object
conduction electron	electron that is free to move away from its atomic orbit
conductor	material that allows electrons to move separately from their atomic orbits; object with properties that allow charges to move about freely within it
continuous charge distribution	total source charge composed of so large a number of elementary charges that it must be treated as continuous, rather than discrete
coulomb	SI unit of electric charge
Coulomb force	another term for the electrostatic force
Coulomb's law	mathematical equation calculating the electrostatic force vector between two charged particles
dipole	two equal and opposite charges that are fixed close to each other
dipole moment	property of a dipole; it characterizes the combination of distance between the opposite charges, and the magnitude of the charges
electric charge	physical property of an object that causes it to be attracted toward or repelled from another charged object; each charged object generates and is influenced by a force called an electric force
electric field	physical phenomenon created by a charge; it "transmits" a force between a two charges
electric force	noncontact force observed between electrically charged objects
electron	particle surrounding the nucleus of an atom and carrying the smallest unit of negative charge
electrostatic attraction	phenomenon of two objects with opposite charges attracting each other
electrostatic force	amount and direction of attraction or repulsion between two charged bodies; the assumption is that the source charges have no acceleration
electrostatic repulsion	phenomenon of two objects with like charges repelling each other
electrostatics	study of charged objects which are not in motion
field line	smooth, usually curved line that indicates the direction of the electric field
field line density	number of field lines per square meter passing through an imaginary area; its purpose is to indicate the field strength at different points in space
induced dipole	typically an atom, or a spherically symmetric molecule; a dipole created due to opposite forces displacing the positive and negative charges

infinite straight wire	straight wire whose length is much, much greater than either of its other dimensions, and also much, much greater than the distance at which the field is to be calculated
insulator	material that holds electrons securely within their atomic orbits
ion	atom or molecule with more or fewer electrons than protons
law of conservation of charge	net electric charge of a closed system is constant
linear charge density	amount of charge in an element of a charge distribution that is essentially one-dimensional (the width and height are much, much smaller than its length); its units are C/m
neutron	neutral particle in the nucleus of an atom, with (nearly) the same mass as a proton
permanent dipole	typically a molecule; a dipole created by the arrangement of the charged particles from which the dipole is created
permittivity of vacuum	also called the permittivity of free space, and constant describing the strength of the electric force in a vacuum
polarization	slight shifting of positive and negative charges to opposite sides of an object
principle of superposition	useful fact that we can simply add up all of the forces due to charges acting on an object
proton	particle in the nucleus of an atom and carrying a positive charge equal in magnitude to the amount of negative charge carried by an electron
static electricity	buildup of electric charge on the surface of an object; the arrangement of the charge remains constant (“static”)
superposition	concept that states that the net electric field of multiple source charges is the vector sum of the field of each source charge calculated individually
surface charge density	amount of charge in an element of a two-dimensional charge distribution (the thickness is small); its units are C/m^2
volume charge density	amount of charge in an element of a three-dimensional charge distribution; its units are C/m^3

area vector	vector with magnitude equal to the area of a surface and direction perpendicular to the surface
cylindrical symmetry	system only varies with distance from the axis, not direction
electric flux	dot product of the electric field and the area through which it is passing
flux	quantity of something passing through a given area
free electrons	also called conduction electrons, these are the electrons in a conductor that are not bound to any particular atom, and hence are free to move around
Gaussian surface	any enclosed (usually imaginary) surface
planar symmetry	system only varies with distance from a plane

spherical symmetry	system only varies with the distance from the origin, not in direction

Key Equations

Coulomb’s law	$\overrightarrow{F_{12}}(r)=\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r_{12}^2}\hat{r_{12}}$
Superposition of electric forces	$\vec{F}(r)=\frac{1}{4\pi\varepsilon_0}Q\sum_{i=1}^{N}\frac{q_i}{r_i^2}\hat{r}_i$
Electric force due to an electric field	$\vec{F}=Q\vec{E}$
Electric field at point P	$\vec{E}(P)\equiv\frac{1}{4\pi\varepsilon_0}\sum_{i=1}^{N}\frac{q_i}{r_i^2}\hat{r}_i$
Field of an infinite wire	$\vec{E}(z)=\frac{1}{4\pi\varepsilon_0}\frac{2\lambda}{z}\hat{k}$
Field of an infinite plane	$\vec{E}=\frac{\sigma}{2\varepsilon_0}\hat{k}$
Dipole moment	$\vec{p}\equiv q\vec{d}$
Torque on dipole in external E-field	$\vec{\tau}=\vec{p}\times\vec{E}$

Definition of electric flux, for uniform electric field	$\Phi=\vec{E}\cdot\vec{A}\rightarrow EAcos\theta$
Electric flux through an open surface	$\Phi=\int_S\vec{E}\cdot\hat{n}dA=\int_S\vec{E}\cdot d\vec{A}$
Electric flux through a closed surface	$\Phi=\oint_S\vec{E}\cdot\hat{n}dA=\oint_S\vec{E}\cdot d\vec{A}$
Gauss’s law	$\Phi=\oint_S\vec{E}\cdot\hat{n}dA=\frac{q_{enc}}{\varepsilon_0}$
Gauss’s Law for systems with symmetry	$\Phi=\oint_S\vec{E}\cdot\hat{n}dA=E\oint_S dA=EA=\frac{q_{enc}}{\varepsilon_0}$
The magnitude of the electric field just outside the surface of a conductor	$E=\frac{\sigma}{\varepsilon_0}$

Summary

5.2 Electric Charge

- There are only two types of charge, which we call positive and negative. Like charges repel, unlike charges attract, and the force between charges decreases with the square of the distance.
- The vast majority of positive charge in nature is carried by protons, whereas the vast majority of negative charge is carried by electrons. The electric charge of one electron is equal in magnitude and opposite in sign to the charge of one proton.
- An ion is an atom or molecule that has nonzero total charge due to having unequal numbers of electrons and protons.
- The SI unit for charge is the coulomb (C), with protons and electrons having charges of opposite sign but equal magnitude; the magnitude of this basic charge is $e\equiv 1.602\times 10^{-19}C$
- Both positive and negative charges exist in neutral objects and can be separated by bringing the two objects into physical contact; rubbing the objects together can remove electrons from the bonds in one object and place them on the other object, increasing the charge separation.
- For macroscopic objects, negatively charged means an excess of electrons and positively charged means a depletion of electrons.
- The law of conservation of charge states that the net charge of a closed system is constant.

5.3 Conductors, Insulators, and Charging by Induction

- A conductor is a substance that allows charge to flow freely through its atomic structure.
- An insulator holds charge fixed in place.
- Polarization is the separation of positive and negative charges in a neutral object. Polarized objects have their positive and negative charges concentrated in different areas, giving them a charge distribution.

5.4 Coulomb's Law

- Coulomb's law gives the magnitude of the force between point charges. It is

$$\overrightarrow{F_{12}}(r)=\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r_{12}^2}\hat{r}_{12}$$

where q_1 and q_2 are two point charges separated by a distance **r**. This Coulomb force is extremely basic, since most charges are due to point-like particles. It is responsible for all electrostatic effects and underlies most macroscopic forces.

5.5 Electric Field

- The electric field is an alteration of space caused by the presence of an electric charge. The electric field mediates the electric force between a source charge and a test charge.
- The electric field, like the electric force, obeys the superposition principle
- The field is a vector; by definition, it points away from positive charges and toward negative charges.

5.6 Calculating Electric Fields of Charge Distributions

- A very large number of charges can be treated as a continuous charge distribution, where the calculation of the field requires integration. Common cases are:
  - one-dimensional (like a wire); uses a line charge density λ
  - two-dimensional (metal plate); uses surface charge density σ
  - three-dimensional (metal sphere); uses volume charge density ρ
- The "source charge" is a differential amount of charge dq. Calculating dq depends on the type of source charge distribution:

$$dq=\lambda dl; dq=\sigma dA; dq=\rho dV\ .$$

- Symmetry of the charge distribution is usually key.
- Important special cases are the field of an "infinite" wire and the field of an "infinite" plane.

5.7 Electric Field Lines

- Electric field diagrams assist in visualizing the field of a source charge.
- The magnitude of the field is proportional to the field line density.
- Field vectors are everywhere tangent to field lines.

5.8 Electric Dipoles

- If a permanent dipole is placed in an external electric field, it results in a torque that aligns it with the external field.
- If a nonpolar atom (or molecule) is placed in an external field, it gains an induced dipole that is aligned with the external field.
- The net field is the vector sum of the external field plus the field of the dipole (physical or induced).
- The strength of the polarization is described by the dipole moment of the dipole, $\vec{p}=q\vec{d}$.

6.2 Electric Flux

- The electric flux through a surface is proportional to the number of field lines crossing that surface. Note that this means the magnitude is proportional to the portion of the field perpendicular to the area.
- The electric flux is obtained by evaluating the surface integral

$$\Phi=\oint_S\vec{E}\cdot\hat{n}dA=\oint_S\vec{E}\cdot d\vec{A}\ ,$$

where the notation used here is for a closed surface S.

6.3 Explaining Gauss’s Law

- Gauss’s law relates the electric flux through a closed surface to the net charge within that surface,

$$\Phi=\oint_S \vec{E}\cdot\hat{n}dA=\frac{q_{enc}}{\varepsilon_0},$$

- where qencqenc is the total charge inside the Gaussian surface S.
- All surfaces that include the same amount of charge have the same number of field lines crossing it, regardless of the shape or size of the surface, as long as the surfaces enclose the same amount of charge.

6.4 Applying Gauss’s Law

- For a charge distribution with certain spatial symmetries (spherical, cylindrical, and planar), we can find a Gaussian surface over which $\vec{E}\cdot\hat{n}=E$, where **E** is constant over the surface. The electric field is then determined with Gauss’s law.
- For spherical symmetry, the Gaussian surface is also a sphere, and Gauss’s law simplifies to $4\pi r^2E=\frac{q_{enc}}{\varepsilon_0}$.
- For cylindrical symmetry, we use a cylindrical Gaussian surface, and find that Gauss’s law simplifies to $2\pi rLE=\frac{q_{enc}}{\varepsilon_0}$.
- For planar symmetry, a convenient Gaussian surface is a box penetrating the plane, with two faces parallel to the plane and the remainder perpendicular, resulting in Gauss’s law being $2AE=\frac{q_{enc}}{\varepsilon_0}$.

6.5 Conductors in Electrostatic Equilibrium

- The electric field inside a conductor vanishes.
- Any excess charge placed on a conductor resides entirely on the surface of the conductor.
- The electric field is perpendicular to the surface of a conductor everywhere on that surface.
- The magnitude of the electric field just above the surface of a conductor is given by $E=\frac{\sigma}{\varepsilon_0}$.

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