Introductory Physics for Scientists and Engineers (II) PHY2049

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Book: University Physics (Vol 2), Young and Freedman, 12th ed.
Chapter 21 – Electric Charge and Electric Field

- Electric Charge
- Conductors, Insulators and Induced Charges
- Coulomb’s Law
- Electric Field and Electric Forces
- Electric Field Calculations
- Electric Field Lines
- Electric Dipoles
1. Electric Charge

**Electrostatics:** interaction between electric charges that are at rest.

(a) Interaction between plastic rods rubbed on fur

Plain plastic rods neither attract nor repel each other ...

... but after being rubbed with fur, the rods repel each other.

Fur  Plastic

(b) Interaction between glass rods rubbed on silk

Plain glass rods neither attract nor repel each other ...

... but after being rubbed with silk, the rods repel each other.

Silk  Glass

(c) Interaction between objects with opposite charges

The fur-rubbed plastic rod and the silk-rubbed glass rod attract each other ...

... and the fur and silk each attracts the rod it rubbed.

Two + charges and two – charges repel each other.

+ charge and – charge attract each other.
Electric Charge and the Structure of Matter

Structure of atoms:  
- electron (-)  
- proton (+)  
- neutron (uncharged)

Combinations of quarks ($\pm \frac{1}{3}\, e$, $\pm \frac{2}{3}\, e \rightarrow e = \text{electron charge}$) = Nucleus

- Electrons (-) held within atom by attractive forces from (+) nucleus.

- Protons & neutrons held by an attractive interaction: strong nuclear force (short range) $>>$ electric repulsion of protons.

- Magnitude of charge of electron = magnitude of charge of proton.
- **Neutral atom**: \# of electrons = \# of protons.
- **Atomic number**: \# of protons or electrons in a neutral atom.
- **Ion**: atom that has lost (+) or gained (-) one or more electrons.
- **Ionization**: process of gaining or loosing electrons.
**Conservation of charge:** the sum of all electric charges in any closed system is constant.

- The magnitude of charge of the electron / proton = unit of charge.

2. **Conductors, Insulators and Induced Charges**

- **Conductor:** material that permits electric charge to move easily from one region to other. Ex. Cu
- **Insulator:** material that does not permit easy movement of charge. Ex: nylon.
- **Semiconductor:** electrical properties intermediate between conduc. & insulat.
**Charging by Induction:**

(a) Uncharged metal ball

(b) Negative charge on rod repels electrons, creating zones of negative and positive induced charge.

(c) Wire lets electron buildup (induced negative charge) flow into ground.

(d) Wire removed; ball now has only an electron-deficient region of positive charge.

(e) Rod removed; electrons rearrange themselves, ball has overall electron deficiency (net positive charge).
Electric forces on uncharged objects:

- A charged object can exert forces on uncharged objects.
- **Polarization**: slight shifting of charge within the molecules of a neutral insulator when a charged object is placed in its proximity.

The motion of static charges about a plastic comb and light bits of paper can cause attractive forces strong enough to overcome the weight of the paper.
3. **Coulomb’s Law**

- The magnitude of the electric force between two point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them.

\[ F = \frac{1}{4\pi\varepsilon_0} \frac{|q_1 q_2|}{r^2} \]

\[ k = 1/(4\pi\varepsilon_0) \sim 9 \times 10^9 \text{ N m}^2/\text{C}^2 \]

\[ \varepsilon_0 = 8.854 \times 10^{-12} \text{ C}^2/\text{N m}^2 \]

**Unit of electric charge:** Coulomb (1 C)

\[ e \sim 1.602 \times 10^{-19} \text{ C} \]

**Unit of electric current** (charge per unit time): Ampere (A)
**Principle of superposition of forces:** When two charges exert forces simultaneously on a third charge, the total force acting on that charge is the vector sum of the two forces that the two charges would exert individually.

### 4. Electric Field and Electric Forces

(a) $A$ and $B$ exert electric forces on each other.

(b) Remove body $B$ ...

... and label its former position as $P$.

(c) Body $A$ sets up an electric field $\vec{E}$ at point $P$.

- A single charge creates an electric field ($\vec{E}$) in the surrounding space. This field cannot exert a net force on the charge that created it.

- The electric force on a charged object is exerted by the electric field created by other charged objects.
Electric field ($\vec{E}$) at P: electric force experienced by a test charge $q_0$ at P, divided by the charge $q_0$.

$$\vec{E} = \frac{\vec{F}_0}{q_0}$$

This definition ignores the force exerted by $q_0$ on the charge distribution of the object of charge $Q$.

To be more rigorous, $q_0$ must be very small $\rightarrow$ take limit when $(q_0 \rightarrow 0)$

The force on a positive test charge $q_0$ points in the direction of the electric field.

The force on a negative test charge $q_0$ points opposite to the electric field.
Electric field of a point charge:

\[ \vec{E} = \frac{1}{4\pi\varepsilon_0} \frac{q}{r^2} \hat{r} \]

- \(\vec{E}\) is not a single vector quantity but a vector field (can vary from point to point).

- **Uniform field**: magnitude and direction of \(\vec{E}\) are constant within a certain region.

- **Electrostatic situation**: when charges are not in motion.

- In electrostatics, *the electric field at every point within the material of a conductor must be zero* (does not need to be zero in a hole inside the conductor).

- If there were \(\vec{E}\) inside conductor it will exert a force on every charge, giving them net motion (not electrostatic situation).
- The electric field of a point charge always points away from a (+) charge but toward a (-) charge.

5. **Electric Field Calculations**

**Superposition of electric fields** (generated by point charges):

\[ \vec{F}_0 = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \ldots = q_0 \vec{E}_1 + q_0 \vec{E}_2 + q_0 \vec{E}_3 + \ldots \]

\[ \vec{E}_0 = \frac{\vec{F}_0}{q_0} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \ldots \]

Electric field at P (on \( q_0 \)) generated by point charges \( q_1, q_2, q_3, \ldots \).
Linear charge density: $\lambda$ (charge per unit length (C/m))
Surface charge density: $\sigma$ (charge per unit area (C/m$^2$))
Volume charge density: $\rho$ (charge per unit volume (C/m$^3$))

6. Electric Field Lines

- Imaginary line in a region of space so that its tangent at any point is in the direction of $\vec{E}$ at that point.

- The spacing of electric field lines indicates the magnitude of $\vec{E}$.

- Electric field lines never intersect → at a point, $\vec{E}$ has a unique direction.

- The magnitude of $\vec{E}$ is different at different points of a field line.

- Electric field lines are not trajectories of charged particles. ($\vec{E}$, $\vec{F}$, $\vec{a}$ tangent to field line, but in a curved path, $\vec{a}$ cannot be tangent to path).
7. Electric Dipoles

- Pair of point charges with equal magnitude and opposite sign.

- The electric dipole moment ($\vec{p}$) is directed from the (-) to the (+) charge.
Force and Torque on an Electric Dipole:

- The net force on an electric dipole in an uniform electric field is zero → $F_+$ and $F_-$ have same magnitude $(qE)$ but opposite direction and their net sum is zero.

- The net torque is not zero. $\vec{\tau} = \vec{r} \times \vec{F}$

$$\tau = r_{\perp} F_+ = r_{\perp} F_- = \left( \frac{d}{2} \right)(\sin \varphi)F = \left( \frac{d}{2} \right)(\sin \varphi)(qE)$$

Same torque magnitude for $F_+$ and $F_-$, same direction.

$\tau_{\text{net}} = (d \sin \varphi)(qE)$

Electric dipole moment: $\vec{p} = q \, d$

Units: C m

$\tau = pE \, \sin \phi$

$\vec{\tau} = \vec{p} \times \vec{E}$
Potential Energy of an Electric Dipole:

\[ dW = \tau \, d\varphi = -pE \sin \varphi \, d\varphi \]

Work done by a torque during \( d\varphi \) → negative sign because torque is in the direction of decreasing angle.

\[ W = \int_{\varphi_1}^{\varphi_2} - (pE \sin \varphi) \, d\varphi = pE \cos \varphi_2 - pE \cos \varphi_1 \]

\[ W = -\Delta U = U_1 - U_2 \]

\[ U = -\vec{p} \cdot \vec{E} = -pE \cos \varphi \]

Potential energy of a dipole in an electric field.