Introductory Physics for Scientists and Engineers (II) PHY2049

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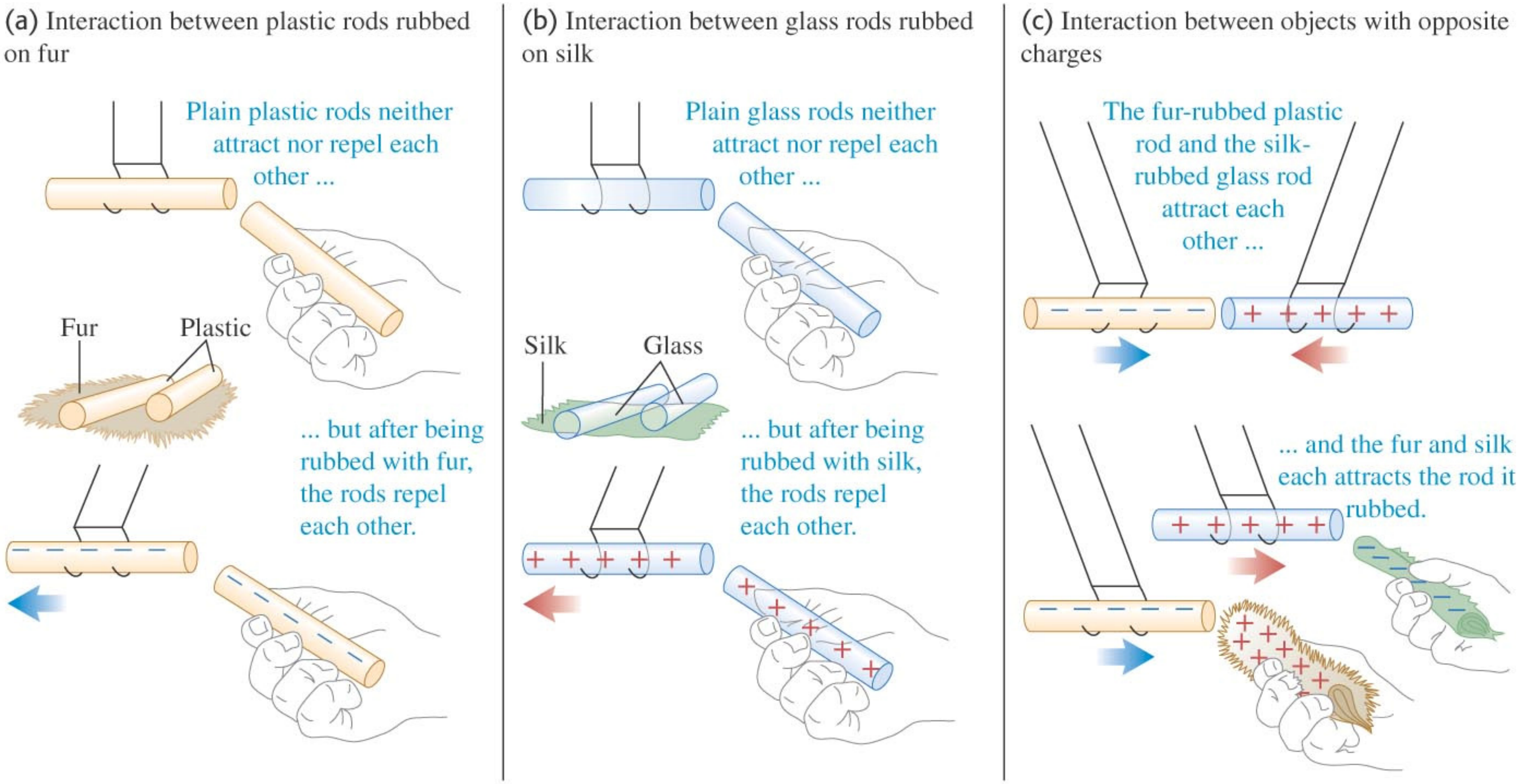
Book: University Physics (Vol 2), Young and Freedman, 12^{th} ed.

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.



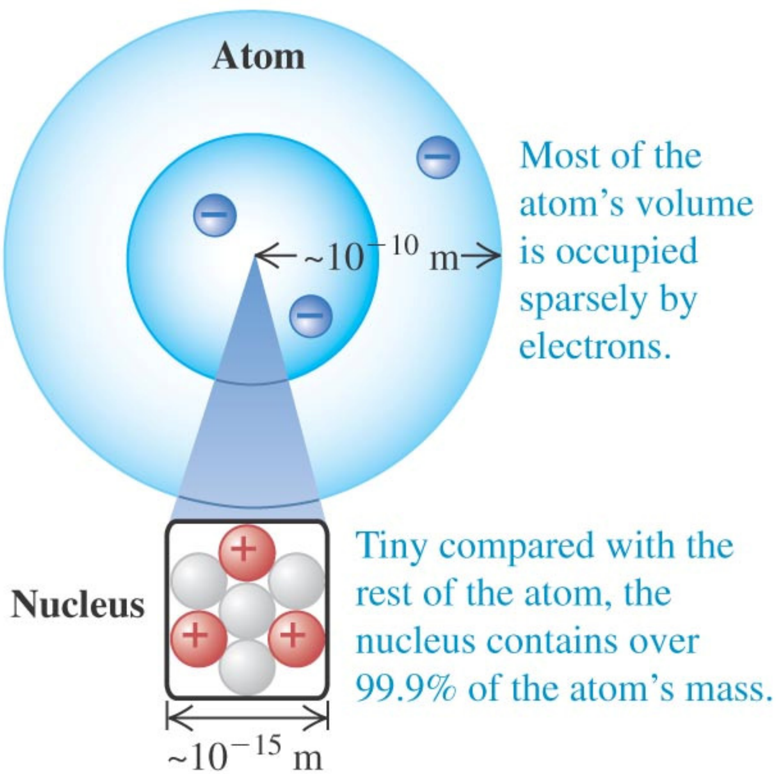
Two + charges and two – charges repel each other.

+ charge and – charge attract each other.

Electric Charge and the Structure of Matter

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

} Combinations of quarks (±1/3 e, ±2/3 e → e = electron charge) = Nucleus

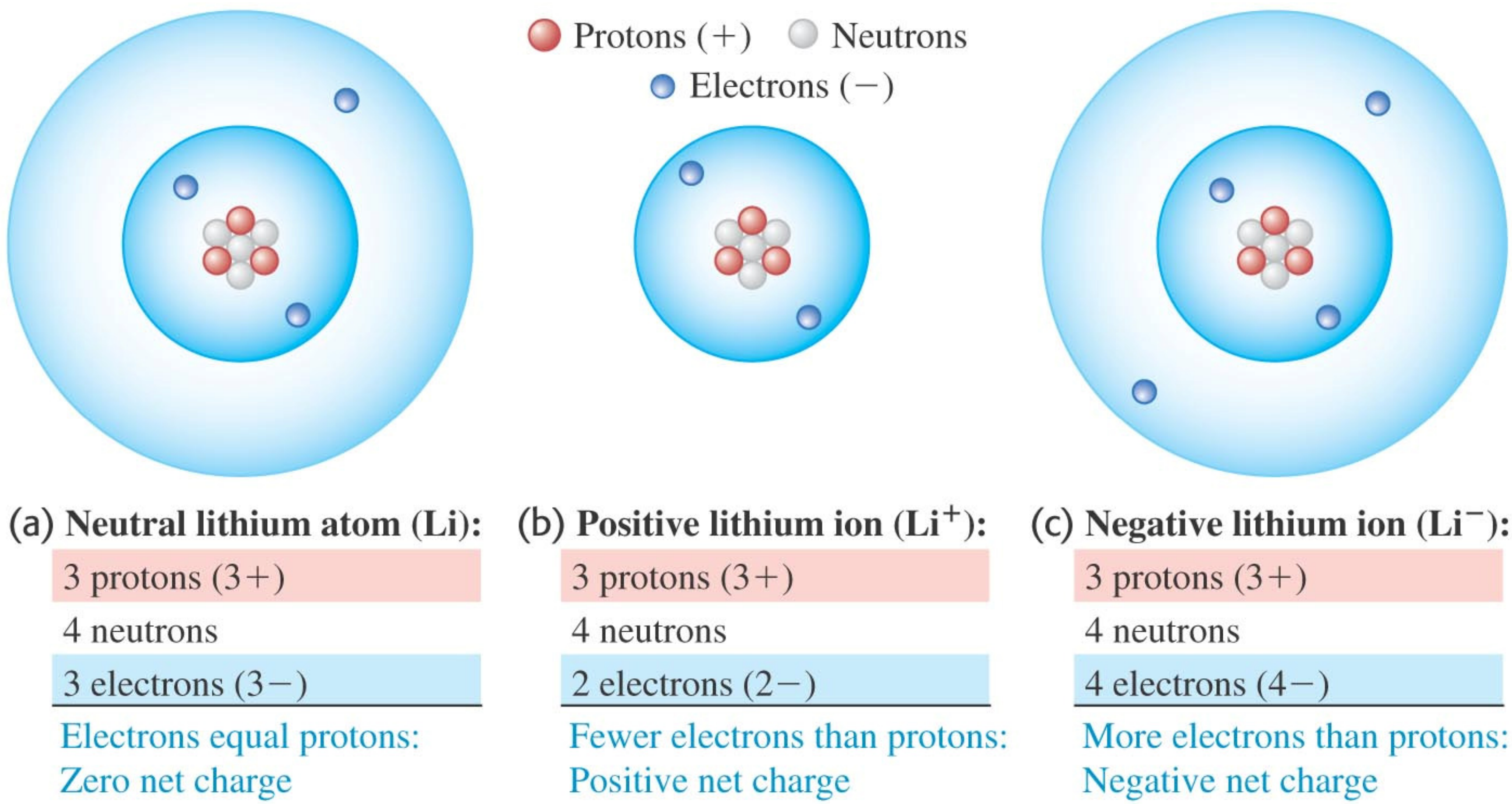


-Electrons (-) held within atom by attractive forces from (+) nucleus.

- 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.

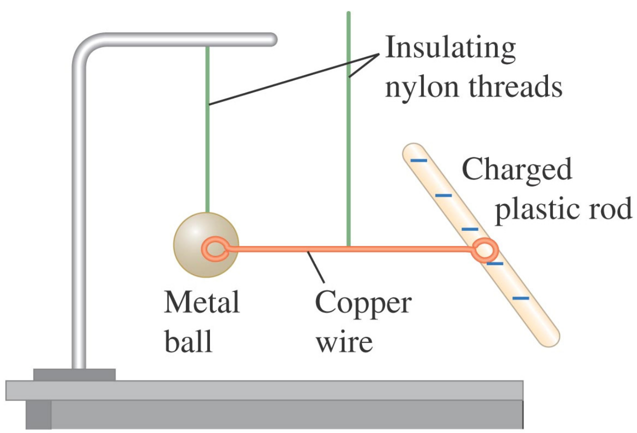


Conservation of charge: the sum of all electric charges in any closed system is constant.

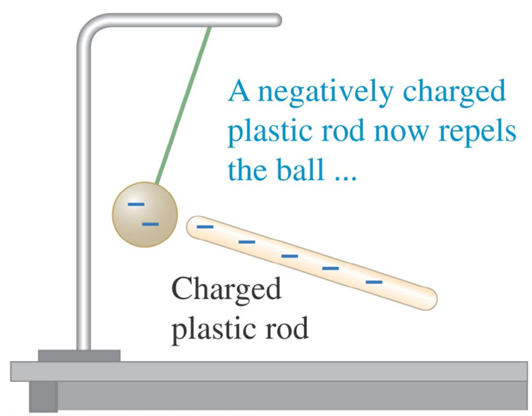
- The magnitude of charge of the electron / proton = unit of charge.

2. Conductors, Insulators and Induced Charges

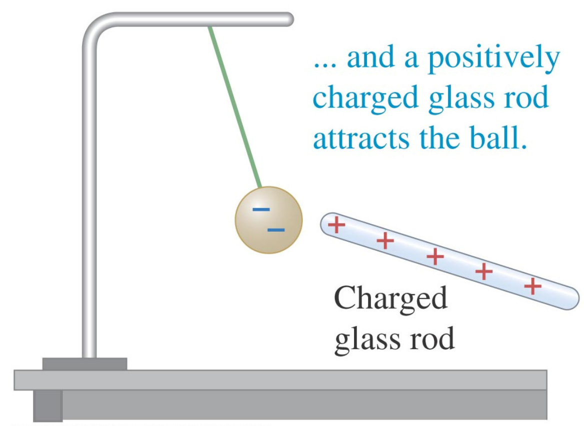
- Conductor: material that permits electric charge to move easily from one region to other. Ex. Cu
- Insulator: material that does not permit easy movement of charge. Ex: nylon.
- Semiconductor: electrical properties intermediate between conduc. & insulat.



The wire conducts charge from the negatively charged plastic rod to the metal ball.

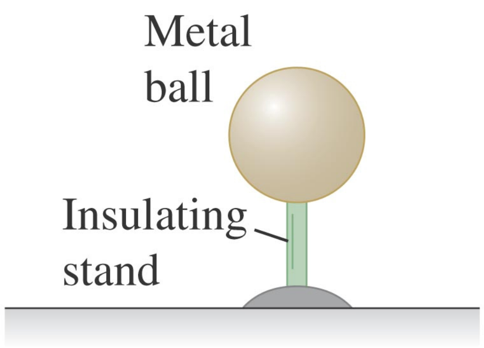


-/- Repulsion

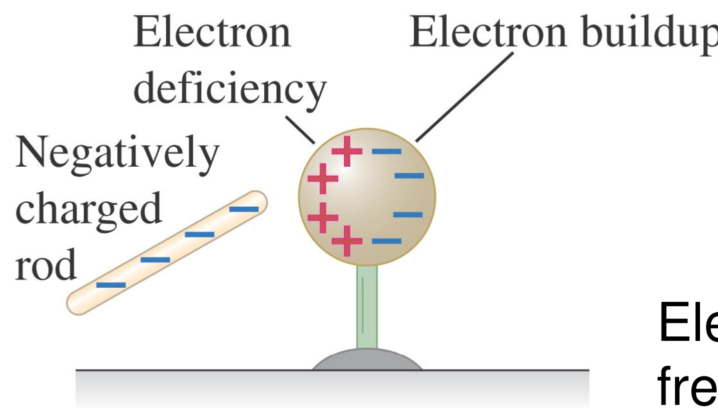


- / + Attraction

Charging by Induction:

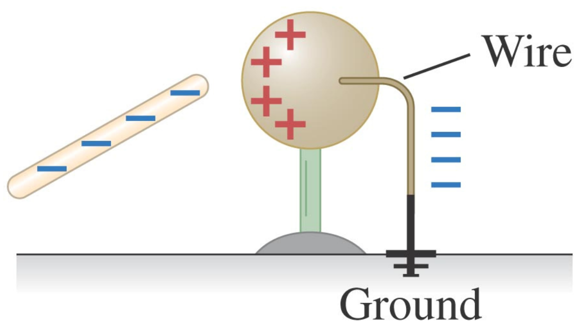


(a) Uncharged metal ball

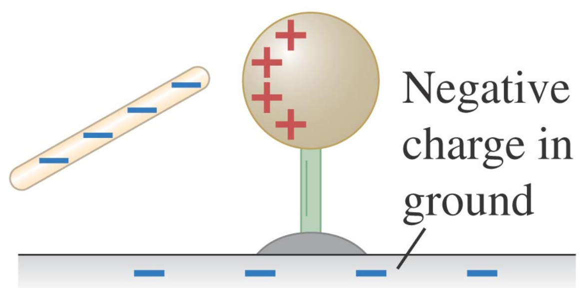


(b) Negative charge on rod repels electrons, creating zones of negative and positive **induced charge**.

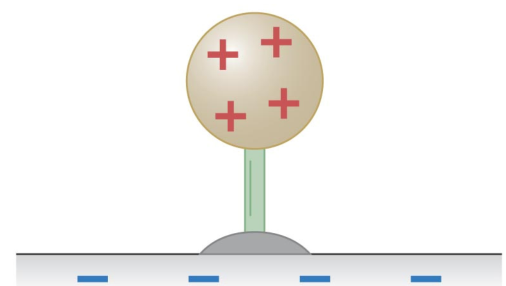
Electrons move freely, and charge can be induced



(c) Wire lets electron build-up (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).

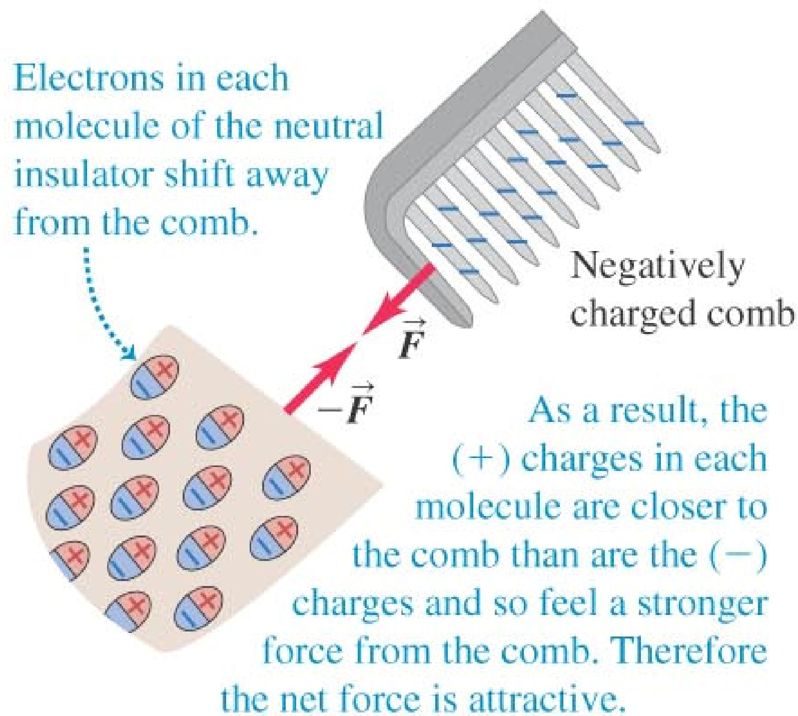
Electric forces on uncharged objects:

- 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.

(a) A charged comb picking up uncharged pieces of plastic

(b) How a negatively charged comb attracts an insulator



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.*

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

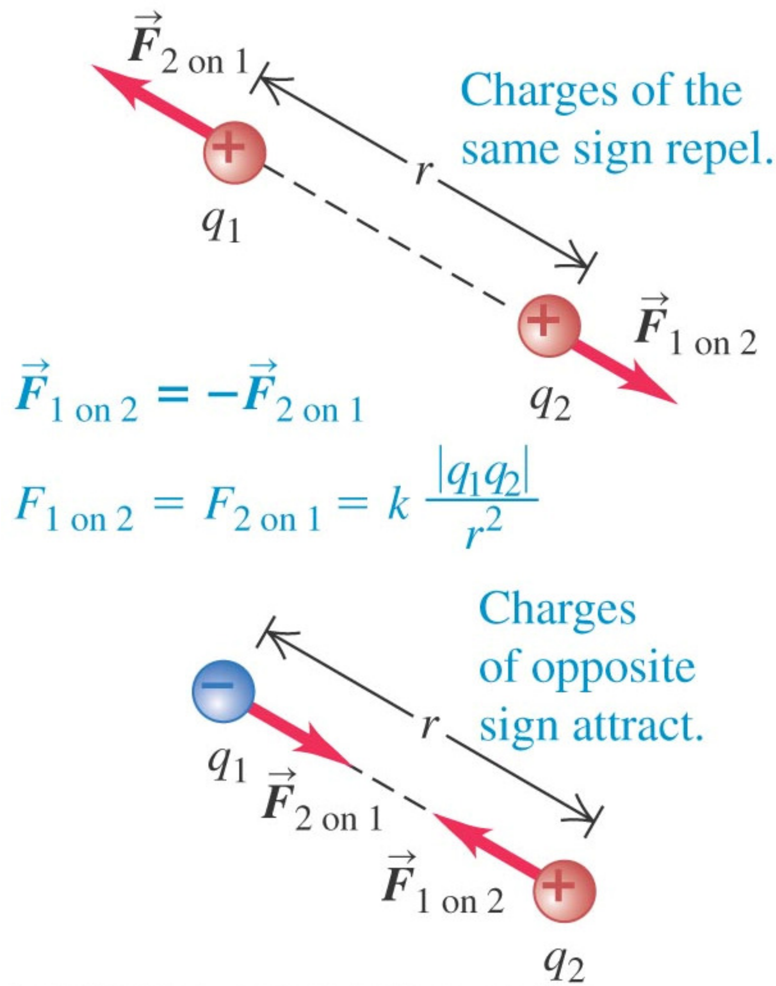
$k = 1/(4\pi\varepsilon_0) \sim 9 \times 10^9$ N m^2/C^2

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

Unit of electric charge: Coulomb (1 C)

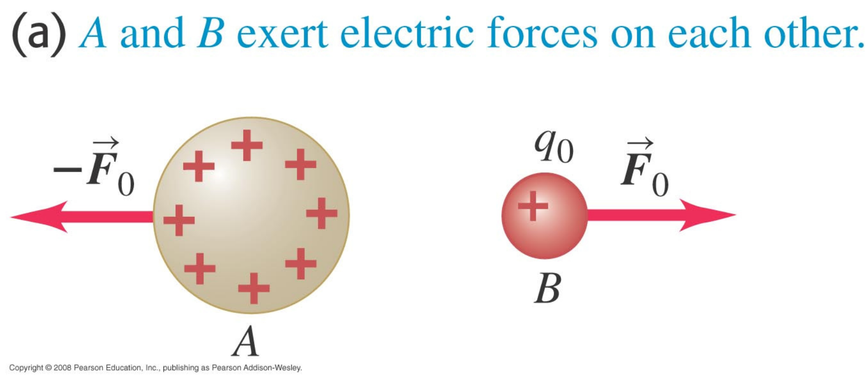
e ~ 1.602×10^{-19} C

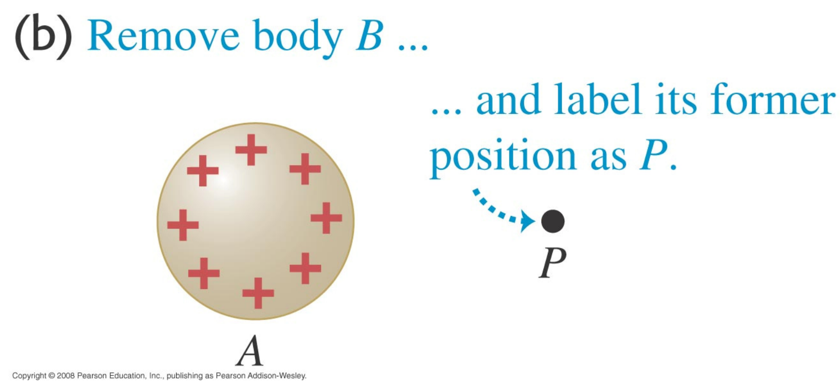
Unit of electric current (charge per unit time): Ampere (A)

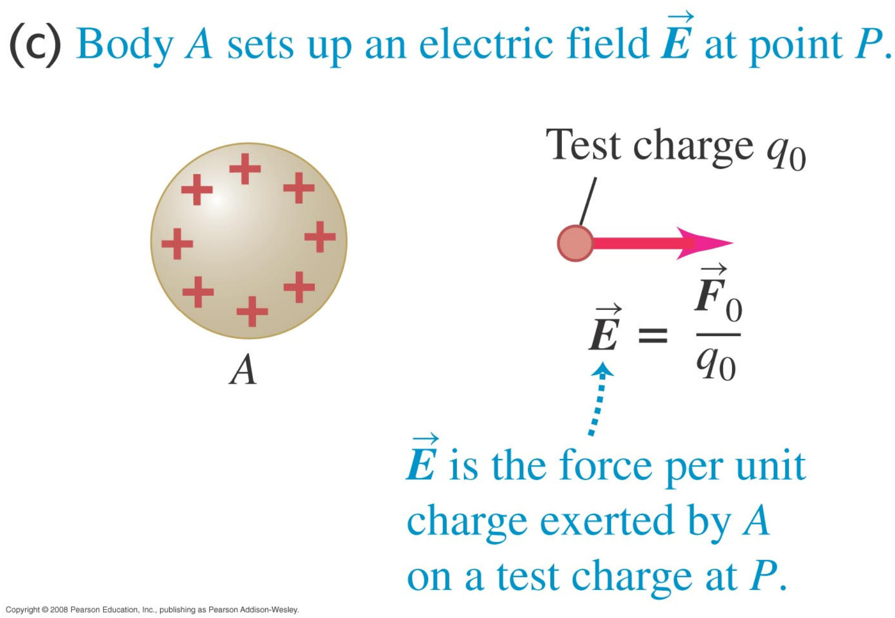


<u>Principle of superposition of forces:</u> when two charges exert forces simultaneously on a third charge, the total force acting on that charge is the vector sum of the two forces that the two charges would exert individually.

4. Electric Field and Electric Forces







- A 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.

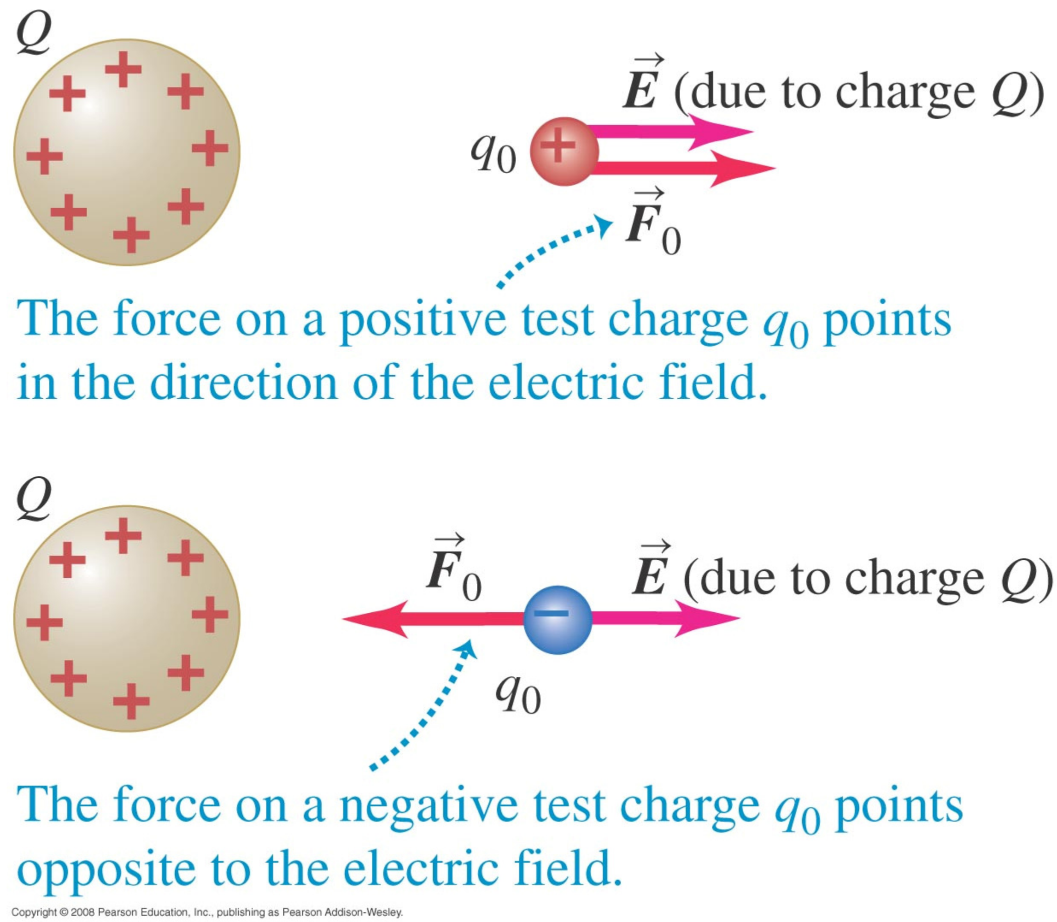
-The electric force on a charged object is exerted by the electric field created by other charged objects.

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 → take limit when (q_0 → 0)



Electric field of a point charge:

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

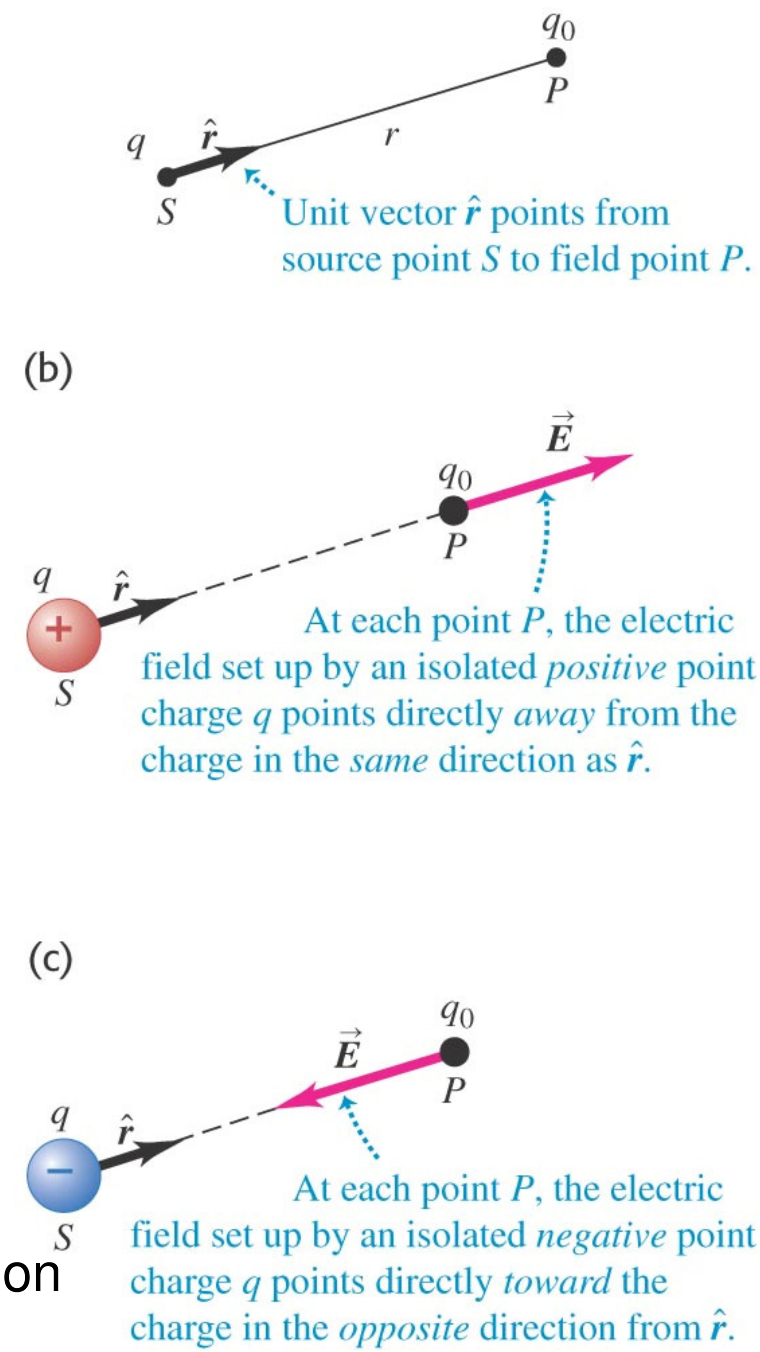
- $\vec{E}$ is not a single vector quantity but a vector field (can vary from point to point).

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

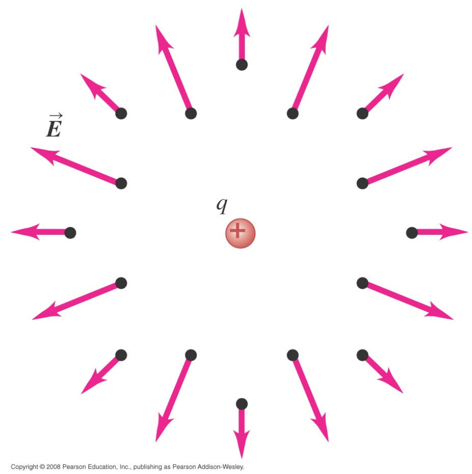
- Electrostatic situation: when charges are not in motion.

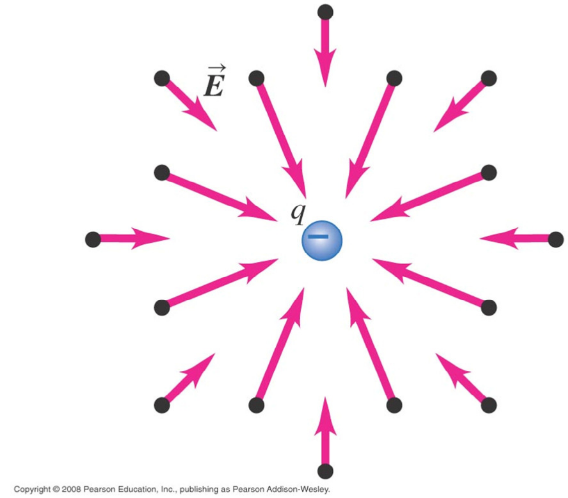
- In electrostatics, *the electric field at every point within the material of a conductor must be zero* (does not need to be zero in a hole hole inside the conductor).

- 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.



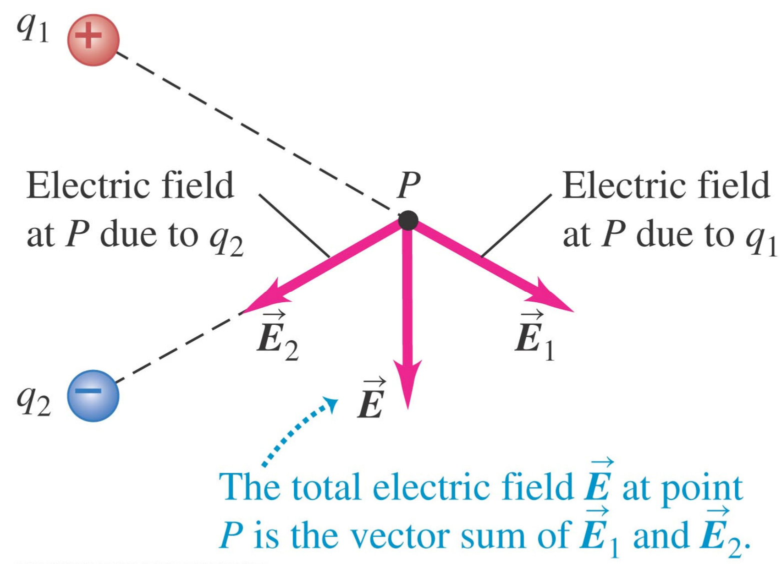


5. Electric Field Calculations

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, …

Linear charge density: λ (charge per unit length (C/m)

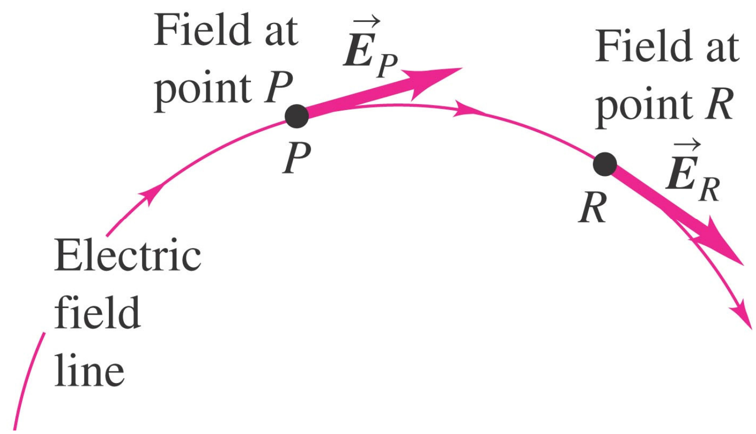
Surface charge density: σ (charge per unit area (C/m²)

Volume charge density: ρ (charge per unit volume (C/m³)

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.

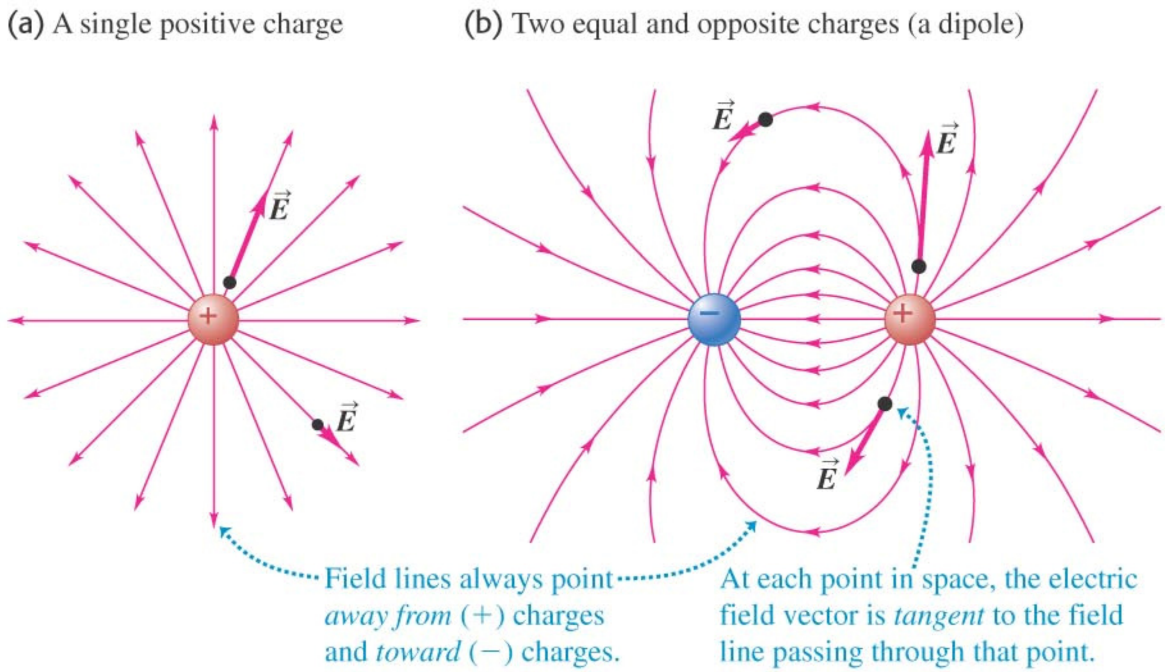
- The spacing of electric field lines indicates the magnitude of $\vec{E}$.



- 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.

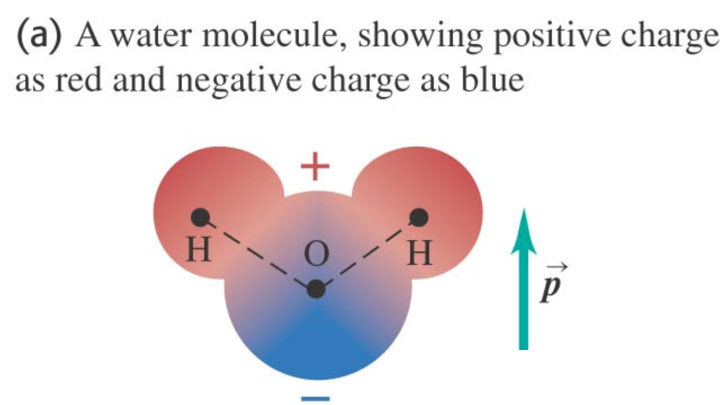
- Electric field lines are not trajectories of charged particles. ($\vec{E}$, $\vec{F}$, $\vec{a}$ tangent to field line, but in a curved path, $\vec{a}$ cannot be tangent to path).



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.

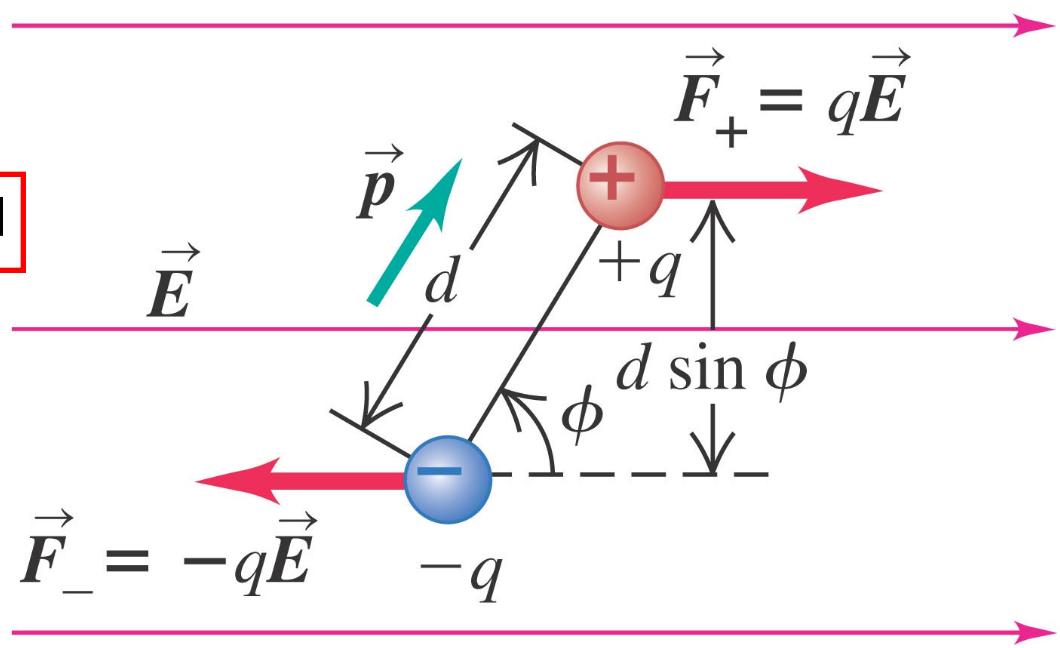
$$\tau_{net} = (d\sin\varphi)(qE)$$

Electric dipole moment: 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 dφ → negative sign because torque is in the direction of decreasing angle.

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

$$W = -\Delta U = U_1 - U_2$$

$$\boxed{U = -\vec{p}\cdot\vec{E} = -pE\cos\varphi}$$

Potential energy of a dipole in an electric field