PHYS11 CH18: Electrostatics

Charges, Fields, Potential, and Capacitors

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Presentation Outline

Outline

Learning Objectives

By the end of this presentation, you will be able to:

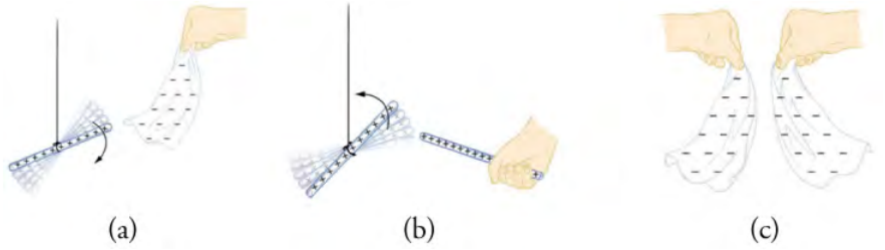
- Describe the nature of electric charge and its conservation
- Apply Coulomb's law to calculate forces between charges
- Define and calculate electric fields around charge distributions
- Understand electric potential and potential energy concepts
- Explain how capacitors work and calculate their capacitance
- Solve problems involving electric forces, fields, potential, and capacitors

Outline

Electrical Charges

Key Concepts

- Two varieties: **positive** and **negative**
- Like charges **repel**, opposite charges **attract**



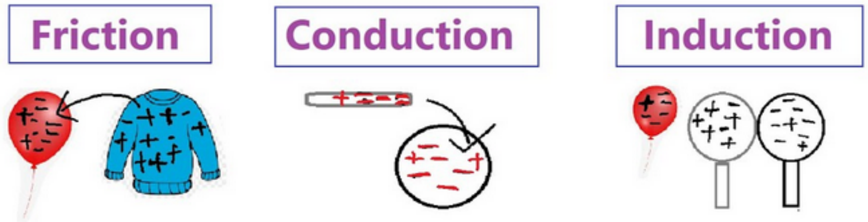
Conductors vs. Insulators

- **Conductors**: Charges move easily **Insulators**: Charges cannot move easily

Transfer of Charge

Three ways to charge objects:

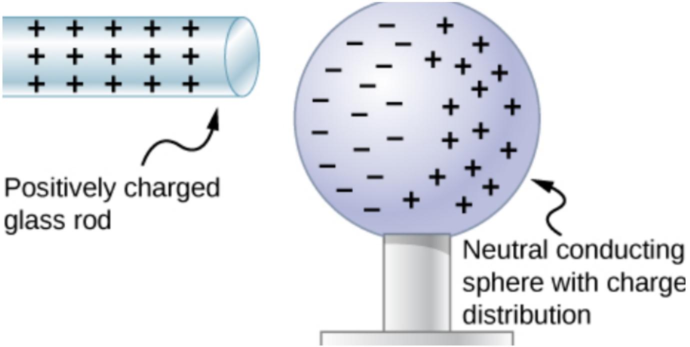
1. **Charging by contact**
   - Direct physical contact between objects
   - Charges transfer from one object to another
2. **Charging by conduction**
   - Charges flow through conducting path
3. **Charging by induction**
   - No contact required
   - Charge separation due to electric field



Polarization

Polarized Objects

- A polarized object may be electrically neutral overall
- But its charge is **unbalanced**:
  - One side has excess **negative** charge
  - The other side has equal magnitude of excess **positive** charge



Outline

Coulomb's Law

Definition

Coulomb's law describes the electrostatic force between charged particles:

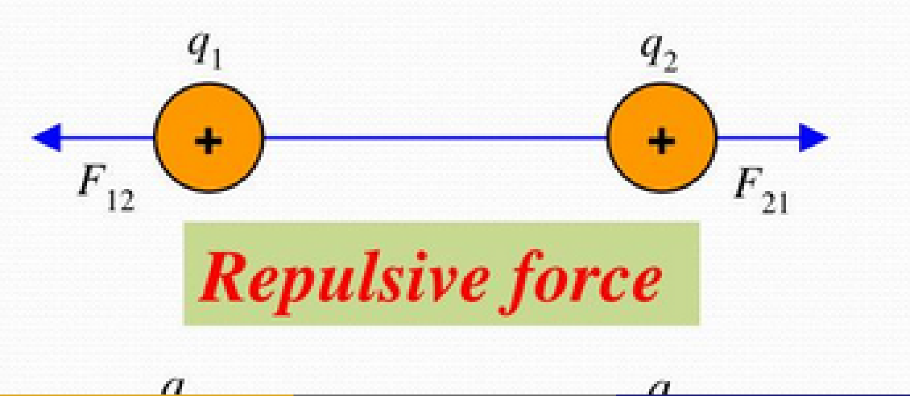
$$\vec{F} = \frac{kq_1q_2}{r^2}\hat{r} \tag{1}$$

where:

- $k = 9 \times 10^9\,\mathrm{N} \cdot \mathrm{m}^2/\mathrm{C}^2$ (Coulomb constant)
- q_1, q_2 are the charges
- r is the distance between charges
- $\hat{r}$ is the unit vector pointing from q_1 to q_2

Properties of Coulomb's Law

- **Inverse square law**: Force $\propto \frac{1}{r^2}$
- Force is **proportional** to the product of charges
- Force interpretation:
  - $F < 0 \rightarrow$ **attractive** force
  - $F > 0 \rightarrow$ **repulsive** force
- Vector nature: Forces act along the line joining the charges



Outline

Electric Field Concept

Definition

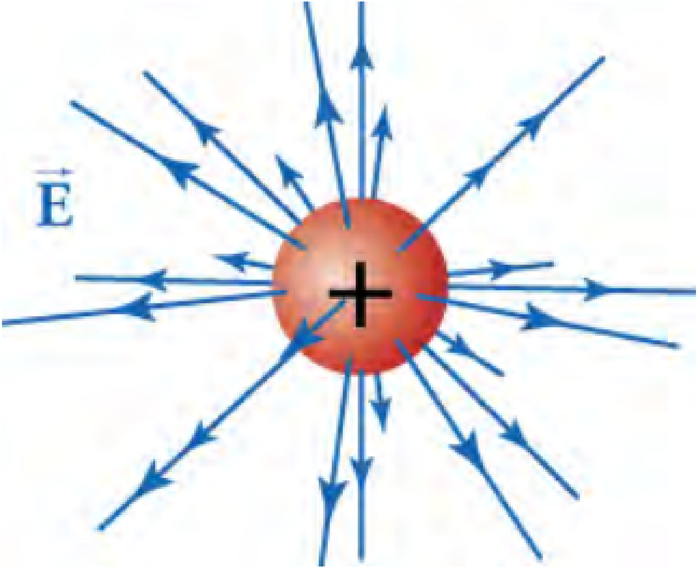
The electric field defines the force per unit charge in the space around a charge distribution:

$$\vec{E} = \frac{\vec{F}}{q_{\text{test}}} \tag{2}$$

Point Charge Electric Field

For a point charge or sphere of uniform charge:

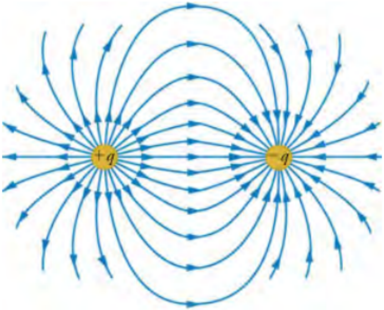
$$E = \frac{kq}{r^2} \tag{3}$$


$\vec{E}$
+

Electric Field Lines

Properties of electric field lines:

- Electric field lines **never cross** each other
- More field lines indicate a **stronger field**
- Lines **start at positive charges** and point away
- Lines **end at negative charges** and point toward them
- In free space, field lines extend to infinity



Outline

Electric Potential Energy

Definition

Electric potential energy is the potential that charges have to do work by virtue of their positions relative to each other.

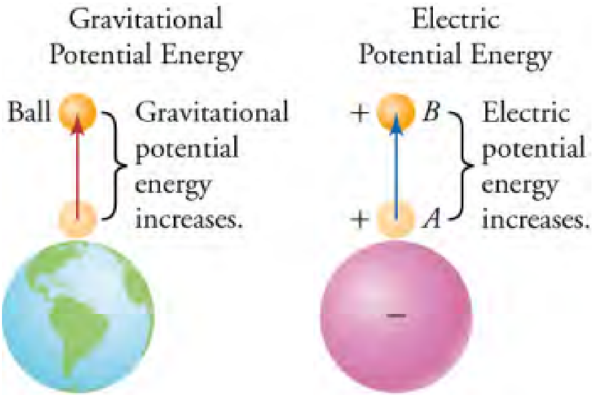
Mathematical Expression

For a charge q in the presence of a point charge Q:

$$U_E = \frac{kqQ}{r} \tag{4}$$

Change in potential energy in constant field:

$$\Delta U_E = -qE(r_f - r_i) \tag{5}$$


Gravitational
Potential Energy
Ball
Gravitational
potential
energy
increases.
Electric
Potential Energy
+
B
+
A
Electric
potential
energy
increases.
−

Electric Potential

Definition

Electric potential is the electric potential energy per unit charge:

$$V = \frac{U_E}{q} \tag{6}$$

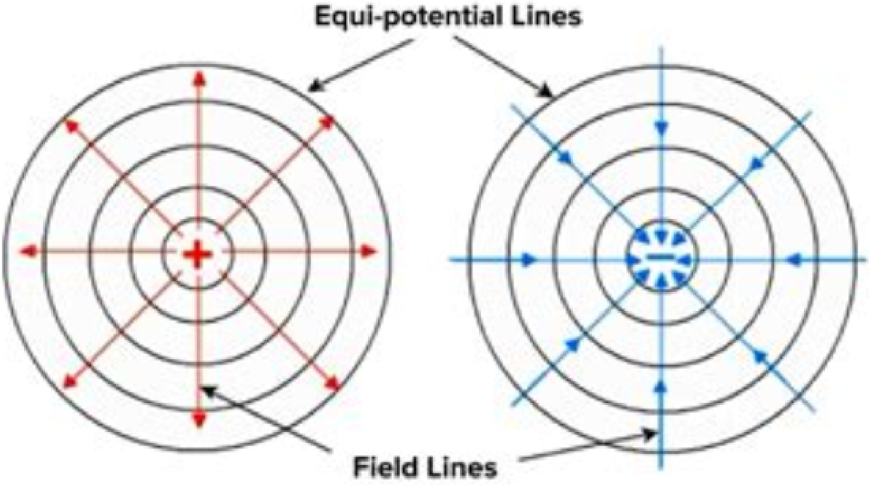
Mathematical Expression

For a point charge Q:

$$V = \frac{kQ}{r} \tag{7}$$

Change in potential in constant field:

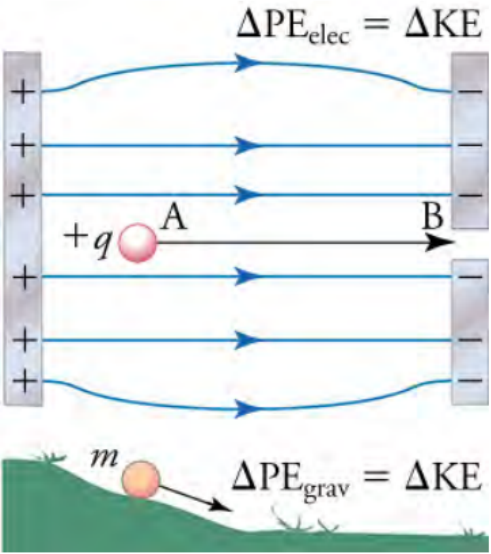
$$\Delta V = -E(r_f - r_i) \tag{8}$$


Equi-potential Lines
+
−
Field Lines

Movement of Charges in Potential

Key Principles

- Potential is always measured between two points
- One reference point may be at infinity ($V = 0$)
- Charges move spontaneously to minimize potential energy:
  - **Positive charges** move from **high** to **low** potential
  - **Negative charges** move from **low** to **high** potential



$\Delta PE_{elec} = \Delta KE$
A
B
$+q$
m
$\Delta PE_{grav} = \Delta KE$

Outline

Capacitors

Definition

A capacitor is a device that stores electric charge and energy in the electric field between its plates.

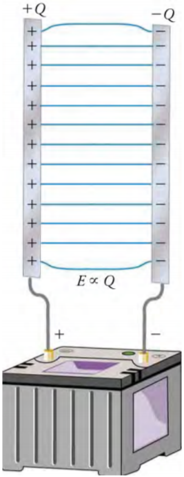
Capacitance

Capacitance is the ratio of charge to potential difference:

$$C = \frac{Q}{V} \tag{9}$$

Capacitance depends only on:

- Geometry of the capacitor
- Materials from which it is made
- **Does not** depend on the voltage



$+Q$
$-Q$
$E \propto Q$
+
−

Parallel-Plate Capacitor

Capacitance Formula

For a parallel-plate capacitor:

$$C = \epsilon_0 \frac{A}{d} \tag{10}$$

where:

- $\epsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F/m}$ (permittivity of free space)
- A is the area of each plate
- d is the separation distance between plates

Energy Storage

Energy stored in a capacitor:

$$U_E = \frac{1}{2} C V^2 \tag{11}$$

Dielectrics

Definition

A dielectric material is an insulator that becomes polarized in an electric field.

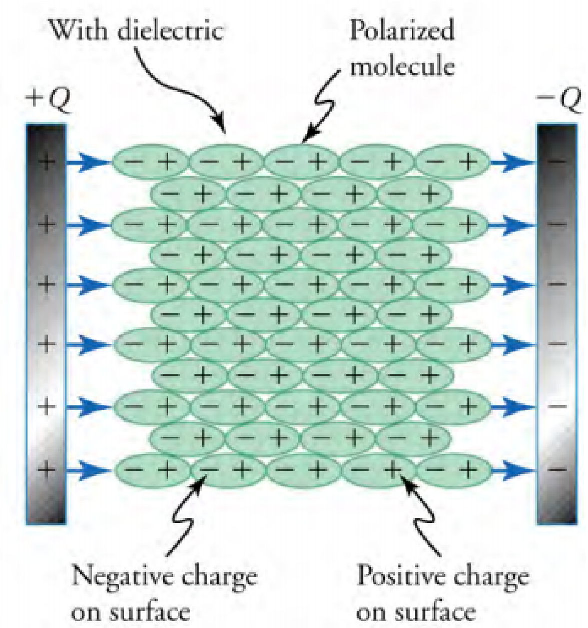
Effects of Dielectrics

Inserting a dielectric between capacitor plates:

- Increases the capacitance by a factor κ (dielectric constant)

$$C = \kappa \epsilon_0 \frac{A}{d} \tag{12}$$

- Reduces the electric field inside the capacitor
- Allows for higher voltage before breakdown


With dielectric
Polarized molecule
+Q
−Q
Negative charge on surface
Positive charge on surface

Outline

Key Equations Summary

Coulomb's Law:

$$F = \frac{kq_1 q_2}{r^2} \tag{13}$$

Electric Field:

$$E = \frac{F}{q_{\text{test}}} \tag{14}$$

Point Charge Field:

$$E = \frac{kq}{r^2} \tag{15}$$

Electric Potential:

$$V = \frac{kQ}{r} \tag{16}$$

Capacitance:

$$C = \frac{Q}{V} \tag{17}$$

Parallel-Plate Capacitor:

$$C = \epsilon_0 \frac{A}{d} \tag{18}$$

Energy Storage:

$$U_E = \frac{1}{2} C V^2 \tag{19}$$

Outline

"I do" Example: Coulomb's Law

Problem

Two point charges $q_1 = +2.0\,\mu\text{C}$ and $q_2 = -3.0\,\mu\text{C}$ are separated by a distance of $0.15\,\text{m}$. Find the magnitude and direction of the electric force between them.

"I do" Example: Coulomb's Law

Problem

Two point charges $q_1 = +2.0\,\mu\text{C}$ and $q_2 = -3.0\,\mu\text{C}$ are separated by a distance of $0.15\,\text{m}$. Find the magnitude and direction of the electric force between them.

Solution

Using Coulomb's law: $F = \frac{kq_1q_2}{r^2}$

$$F = \frac{(9\times10^9\ \text{N}\cdot\text{m}^2/\text{C}^2)(2.0\times10^{-6}\ \text{C})(-3.0\times10^{-6}\ \text{C})}{(0.15\,\text{m})^2}$$

$$F = \frac{(9\times10^9)(-6.0\times10^{-12})}{0.0225}$$

$$F = -2.4\times10^{-3}\ \text{N}$$

The negative sign indicates an attractive force. The force on q_1 is directed toward q_2, and the force on q_2 is directed toward q_1.

"We do" Example: Electric Field

Problem

Three point charges are arranged on the x-axis: $q_1 = +2.0\,\mu\text{C}$ at $x = 0$, $q_2 = -3.0\,\mu\text{C}$ at $x = 0.15\,\text{m}$, and $q_3 = +1.0\,\mu\text{C}$ at $x = 0.30\,\text{m}$. Find the electric field at point P located at $x = 0.45\,\text{m}$.

"We do" Example: Electric Field

Problem

Three point charges are arranged on the x-axis: $q_1 = +2.0\,\mu\text{C}$ at $x = 0$, $q_2 = -3.0\,\mu\text{C}$ at $x = 0.15\,\text{m}$, and $q_3 = +1.0\,\mu\text{C}$ at $x = 0.30\,\text{m}$. Find the electric field at point P located at $x = 0.45\,\text{m}$.

Solution Approach

1. Calculate the electric field due to each charge at point P

$$E_1 = \frac{kq_1}{r_1^2} = \frac{k(+2.0 \times 10^{-6})}{(0.45)^2} \text{ (pointing right)} \tag{20}$$

$$E_2 = \frac{kq_2}{r_2^2} = \frac{k(-3.0 \times 10^{-6})}{(0.30)^2} \text{ (pointing left)} \tag{21}$$

$$E_3 = \frac{kq_3}{r_3^2} = \frac{k(+1.0 \times 10^{-6})}{(0.15)^2} \text{ (pointing right)} \tag{22}$$

2. Find the total field by superposition: $\vec{E}_{\text{total}} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3$

"You do" Example: Capacitor

Problem

A parallel-plate capacitor has plates with an area of $0.0025\,\mathrm{m}^2$ separated by a distance of $0.5\,\mathrm{mm}$.
(a) Calculate the capacitance of this capacitor.
(b) If the capacitor is connected to a $12\,\mathrm{V}$ battery, determine the charge stored on each plate.
(c) Calculate the energy stored in the capacitor.
(d) If a dielectric with $\kappa = 3.0$ is inserted between the plates, find the new capacitance.

Hints

- Use $C = \epsilon_0 \frac{A}{d}$ for part (a)
- Apply $Q = CV$ for part (b)
- Use $U_E = \frac{1}{2}CV^2$ for part (c)
- Remember that with a dielectric, $C = \kappa\epsilon_0 \frac{A}{d}$

Outline

Summary: Key Takeaways

Electrical Charges & Coulomb's Law

- Electric charge is conserved; like charges repel, unlike attract
- Coulomb's law: $F = \frac{kq_1 q_2}{r^2}$

Electric Field & Potential

- Electric field: force per unit charge; $E = \frac{F}{q_{\text{test}}}$
- Electric potential: potential energy per unit charge; $V = \frac{U_E}{q}$

Capacitors & Dielectrics

- Capacitance $C = \frac{Q}{V}$; energy storage $U_E = \frac{1}{2}CV^2$
- Parallel-plate capacitor: $C = \epsilon_0 \frac{A}{d}$
- Dielectrics increase capacitance by a factor κ

Thank You!

Questions?

Practice problems: Textbook Chapter 18