PHYS12 CH 18: Electric Charge and Electric Field

Understanding fundamental electrostatic principles

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Outline

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Learning Objectives

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

- Describe the fundamental properties of electric charge
- Distinguish between conductors and insulators
- Apply Coulomb's Law to calculate electrostatic forces
- Explain the concept of an electric field
- Interpret electric field lines and their meaning
- Understand electrostatic equilibrium in conductors
- Identify practical applications of electrostatics

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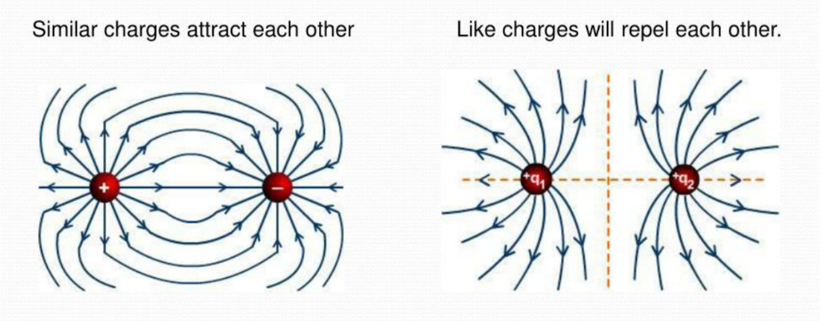
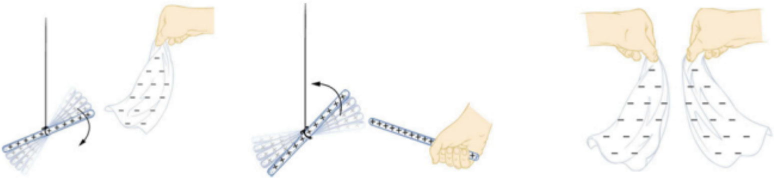
Electric Charge

- Only two types of charge exist:
  - Positive charge (protons)
  - Negative charge (electrons)
- Like charges repel, unlike charges attract
- Force decreases with the square of distance
- Smallest unit of charge: elementary charge
  - $e = 1.60 \times 10^{-19}$ C

Charge Interaction





(a) (b) (c)

Conservation of Charge

Law of Conservation of Charge

The net charge of an isolated system remains constant.

Charge cannot be created or destroyed.

- When an object becomes charged, it's due to a transfer of charge
- Common range for static electricity: nanocoulombs to microcoulombs
- Most charging results from separation of existing charges
- Example: Rubbing two neutral objects can transfer electrons

Important Equation

$$Q_{system} = \sum q_i = \text{constant}$$

Charge Notation and Sources

- **Big Q** (Q):
  - Represents total or net charge
  - Measured in coulombs (C)
  - Used for describing overall charge of objects or systems
  - Source: Accumulation of multiple elementary charges
- **Little q** (q):
  - Represents individual charge or point charge
  - Used in force calculations between charges
  - Source: Individual charged particles or concentrated charge
- **Point charge** (a particle having a charge):
  - Idealized model where charge is concentrated at a single point

$$Q = N \cdot e \tag{1}$$

$$F = k\frac{q_1 q_2}{r^2} \tag{2}$$

$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}\hat{r} \tag{3}$$

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Conductors vs. Insulators

Conductors:

- Allow free movement of charge
- Electrons move easily through material
- Examples: metals (copper, aluminum)
- Excess charge distributes on surface

Insulators:

- Restrict movement of charge
- Electrons tightly bound to atoms
- Examples: rubber, plastic, glass
- Charge remains at placement location

Semiconductors

Materials with properties between conductors and insulators (e.g., silicon, germanium)

Polarization and Charging Methods

Polarization:

- Separation of positive and negative charges in a neutral object
- Induced by external electric field
- Creates local charge imbalances without overall charging

Charging Methods:

- Charging by contact:
  - Direct touch transfers charge
  - Objects acquire same type of charge
- Charging by induction:
  - No direct contact required
  - Requires grounding during process
  - Objects acquire opposite type of charge

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Coulomb's Law

Coulomb's Law

The electrostatic force between two point charges is:

$$\vec{F} = k\frac{|q_1 q_2|}{r^2}\hat{r}(18.1) \tag{4}$$

where:

- $k = 8.99 \times 10^9$ N·m^2/C^2 (Coulomb constant)
- q_1, q_2 are charges in coulombs
- r is the distance between charges in meters
- $\hat{r}$ is the unit vector pointing from q_1 to q_2

- Inverse-square relationship with distance
- Similar to gravitational force, but much stronger
- Can be attractive (opposite charges) or repulsive (like charges)

I Do: Coulomb's Law Example

Example Problem

What is the repulsive force between two pith balls that are 8.00 cm apart and have equal charges of -30.0 nC?

I Do: Coulomb's Law Example

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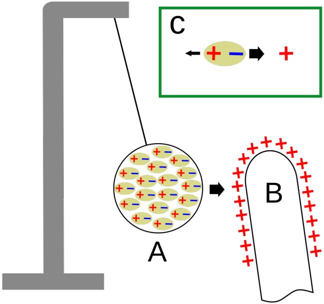

I Do: Coulomb's Law Example

Example Problem

What is the repulsive force between two pith balls that are 8.00 cm apart and have equal charges of -30.0 nC?

Solution

$$
\begin{aligned}
F &= k\frac{|q_1 q_2|}{r^2} && (5)\\
&= (8.99 \times 10^9 \ \mathrm{N \cdot m^2/C^2})\frac{(30.0 \times 10^{-9} \ \mathrm{C})^2}{(0.0800 \ \mathrm{m})^2} && (6)\\
&= (8.99 \times 10^9)\frac{9.00 \times 10^{-16}}{6.40 \times 10^{-3}} && (7)\\
&= 1.264 \times 10^{-3} \ \mathrm{N} \approx 1.27 \times 10^{-3} \ \mathrm{N} && (8)
\end{aligned}
$$

- The force is repulsive because the charges have the same sign
- This is a very small force, but measurable with sensitive equipment

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The Electric Field

Electric Field Definition

The electric field $\vec{E}$ at a point in space is defined as the electric force $\vec{F}$ per unit charge that would act on a small positive test charge q_0 placed at that point:

$$\vec{E} = \frac{\vec{F}}{q_0}(18.2) \tag{9}$$

- Units: N/C (newtons per coulomb)
- A vector quantity with magnitude and direction
- Direction is the same as force on a positive test charge
- Exists at all points in space around charged objects
- Multiple electric fields add vectorially

Electric Field of a Point Charge

Electric Field of a Point Charge

The electric field created by a point charge Q at a distance r is:

$$\vec{E} = k\frac{|Q|}{r^2}\hat{r}(18.3) \qquad (10)$$

where $\hat{r}$ points away from a positive charge or toward a negative charge.

- Field strength decreases with the square of distance
- Field extends to infinity, but becomes weaker with distance
- The field of multiple charges is the vector sum of individual fields:

$$\vec{E}_{total} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \ldots (18.4) \qquad (11)$$

We Do: Electric Field Example

Example Problem

What is the magnitude and direction of an electric field that exerts a 2.00×10^{-5} N upward force on a -1.75 C charge?

Let's Solve Together

Using the definition of electric field: $\vec{E} = \frac{\vec{F}}{q}$

$$E = \frac{F}{|q|} \tag{12}$$

$$= \frac{2.00 \times 10^{-5}\ \text{N}}{1.75 \times 10^{-6}\ \text{C}} \tag{13}$$

$$= 11.4\ \text{N/C} \tag{14}$$

For direction: Since the charge is negative and the force is upward, the electric field must be downward.
Remember: $\vec{F} = q\vec{E}$, and negative charges experience force in the direction opposite to the electric field.

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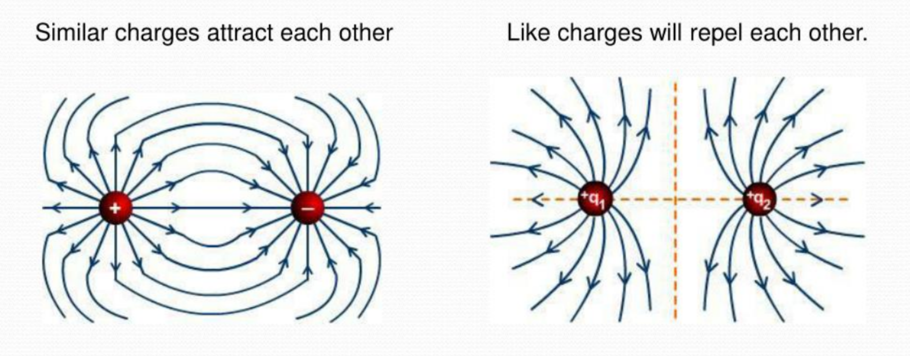
Electric Field Lines: Visualization

Electric Field Lines

Visual representation of electric fields with the following properties:

- Start on positive charges, end on negative charges
- Direction of field is tangent to the line at any point
- Density of lines proportional to field strength
- Number of lines from/to a charge proportional to charge magnitude
- Lines never cross (field has unique direction at any point)


Similar charges attract each other
+
–
Like charges will repel each other.
$+q_1$
$+q_2$

Field Line Patterns

Single Point Charge:

- Positive charge: lines point outward
- Negative charge: lines point inward
- Radially symmetric pattern

Two Like Charges:

- Lines repel each other
- Field-free point between charges

Two Unlike Charges:

- Lines connect charges
- Concentrated between charges
- Form dipole field at distance

Electric Dipole:

- Equal + and - charges separated by small distance
- Important in molecular interactions

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Conductors in Electrostatic Equilibrium

Key Properties

When a conductor reaches electrostatic equilibrium:

- The electric field inside the conductor is zero
- Any excess charge resides entirely on the surface
- The electric field at the surface is perpendicular to the surface
- Charge concentrates at surfaces with greater curvature
- Charge density is highest at sharp points and edges

Implications

This explains why lightning rods have sharp points and why Faraday cages shield their interiors from external fields.

Lightning Rods and Faraday Cages

Lightning Rods:

- Metal rod with sharp point
- Facilitates charge dissipation into air
- Provides safe path to ground for lightning

Faraday Cages:

- Conducting enclosure shields interior from external field
- External charges induce surface charges that cancel internal field
- Applications: elevators, cars, microwave ovens, sensitive equipment
- Protection during lightning storms

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Practical Applications of Electrostatics

Van de Graaff Generator:

- Research and educational tool
- Generates high voltage, low current
- Can produce millions of volts

Photocopiers & Laser Printers:

- Use charged drum
- Toner particles attracted to charged regions
- Heat fuses toner to paper

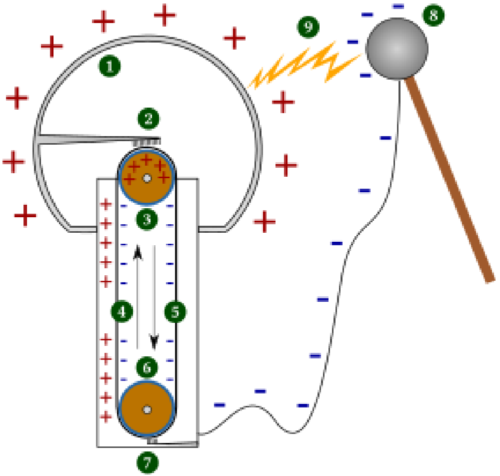
Ink-Jet Printers:

- Electrically charge ink droplets
- Deflect droplets to precise positions

Electrostatic Air Filters:

- Charge air particles
- Attract charged particles to plates
- Remove pollutants from air

Van de Graaff Generator



1. hollow metal sphere
2. upper electrode
3. upper roller (for example an acrylic glass)
4. side of the belt with positive charges
5. opposite side of belt, with negative charges
6. lower roller (metal)
7. lower electrode (ground)
8. spherical device with negative charges
9. spark produced by the difference of potentials

You Do: Coulomb's Law Challenge

Problem to Solve

Two point charges are brought closer together, increasing the force between them by a factor of 25. By what factor was their separation decreased?

- Step 1: Recall Coulomb's law: $F = k\frac{|q_1 q_2|}{r^2}$
- Step 2: Set up ratio of forces: $\frac{F_2}{F_1} = 25$
- Step 3: Consider how distance affects the force
- Step 4: Solve for the ratio of distances

Work on this for 2 minutes

We'll discuss the solution afterward.

You Do: Solution

Solution

From Coulomb's law:

$$F_1 = k\frac{|q_1 q_2|}{r_1^2} \quad \text{and} \quad F_2 = k\frac{|q_1 q_2|}{r_2^2} \tag{15}$$

$$\frac{F_2}{F_1} = \frac{r_1^2}{r_2^2} = 25 \tag{16}$$

$$\frac{r_1}{r_2} = \sqrt{25} = 5 \tag{17}$$

- Since $\frac{r_1}{r_2} = 5$, the separation was decreased by a factor of 5
- Remember: Force is inversely proportional to distance squared
- This is why the force increases so dramatically with small distance changes

Summary: Key Concepts

Electric Charge:

- Two types: positive and negative
- Like charges repel; unlike attract
- Conserved in isolated systems

Coulomb's Law:

- $F = k\frac{|q_1 q_2|}{r^2}$
- Inverse-square relationship

Electric Field:

- $E = \frac{F}{q}$ (force per unit charge)
- $E = k\frac{|Q|}{r^2}$ for point charge
- Field lines visualize direction and strength

Conductors:

- Excess charge on surface
- Zero field inside at equilibrium
- Charge concentrates at sharp points

Questions?

Thank you for your attention!