In this chapter we will cover

- Properties of Electric Charges
- Conductors and insulators
- Coulomb’s Law

21-1 What is physics?

- Many devices depend on the physics of electromagnetism (combination of electric and magnetic phenomena). This physics is the root of computers, television, radio, telecommunications, house lighting, etc.

- The sciences of electricity and magnetism developed separately for centuries—until 1820, before exploring the connection between them (physics of Electromagnetism)

- Phenomena of electric force discovered in ancient Greek times (700 BC), who discovered that if a piece of amber (آを集め) is rubbed and then brought near bits of straw (قشر), the straw will jump to the amber due to this electric force

- Presence of electric force is due to the presence of what is called Electric Charge

21-2, 5, 6: Properties of electric charge

**Electric charge** is an intrinsic property of fundamental particles (atoms) making up the materials.

**Types of charges:**

- Positive charge (+ve)
- Negative charge (-ve)

**Charged object**

- When +ve and –ve charges are equal within object → electrically neutral object.
- If object charge is not balanced → charged object
- Examples: whenever two non-conducting substances are rubbed together
  * Hard rubber rubbed with fur → negative charge (-ve)
  * Glass rod rubbed with silk → positive charge (+ve)

- The charge manifest itself by attraction or repulsion of charged materials

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21-2, 5, 6: Properties of electric charge

Consider a positively charged glass rod suspended by a thread

a) It is attracted to a -ve charged plastic rod.

b) It is repelled by another +ve charged glass rod.

Two types of charges named by Benjamin Franklin (1706-1790) as positive and negative

→ Like charges repel and Unlike charges attract
21-2, 5, 6: Properties of electric charge

- Electric charge is not created.
- Usually, negative charge is transferred from one object to the other.
  ➔ Electric charge is always **conserved**

When a glass rod is rubbed with silk, electrons are transferred from the glass to the silk.

- Silk will have –ve charge and glass will have equal amount of +ve charge
- **Grounding**: The "Earth" is considered an infinite sink of charges

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**Robert Millikan found, in 1909, that all charges are integer multiple of an elementary charge e**

⇒ Charge is **quantized** ➔ Any charged object must have a charge of ±e, or ±2e, or ±3e, etc., but not say ±1.5e.

⇒ $q = \pm ne$ (n = 1, 2, 3, … is an integer)

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<td>p</td>
<td>$+e$</td>
</tr>
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<td>Neutron</td>
<td>n</td>
<td>0</td>
</tr>
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The coulomb unit is derived from the SI unit **ampere for electric current**

\[
i = \frac{dq}{dt} \quad (\text{electric current}) \quad dq = i \, dt \quad \text{1 C} = (1 \text{A})(1 \text{s})
\]

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21-2, 5, 6: Properties of electric charge

**What Carries Charge?**

- Electric charge come from the particles making up the basic unit of matter (the atom)
- Atoms consist of:
  - +ve charge is that carried by **protons**
  - -ve charge is that carried by **electrons**
  - electrically neutral **neutrons** in atom.

The protons and neutrons are packed tightly together in a central nucleus.

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21-2, 5, 6: Properties of electric charge

**Charge is carried by electrons and protons.**

- Can be **positive** or **negative**.

- **Like** charges repel, **opposite** charges attract.

- Total charge in a system is **conserved**.

- Charges come in **discrete** quantities (quantized).

- Charges are measured in **Coulombs (C)**.

- Usually denoted by $q$. 

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**Table 21-1**

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21.3 Conductors and Insulators

- **Conductors**
  - Charges move freely.
  - Like Metals (Cu, Ag, Al)

- **Nonconductors or Insulators**
  - No movement of charges within the object (only very few can move).
  - Like rubber, plastics, and glass

- **Semi-conductors**
  - Limited number of free carriers (intermediate between conductors and insulators).
  - Like Silicon and Germanium

- **Superconductors**
  - Perfect conductors, allowing charge to move without any difficulty.

The properties of conductors and insulators are due to the structure and electrical nature of atoms.

21.4 Coulomb's Law

- Coulomb’s law: when two charges brought together and separated by a distance \( r \), there exist an electric force between these charges.

- Charles Coulomb discovered in 1785 the fundamental law of electrical force between two stationary charged particles using torsion balance.

- An electric force has the following properties:
  - Inversely proportional to the square of the separation, \( r \), between the particles, and is along a line joining them.
  - Proportional to the product of the magnitudes of the charges \( |q_1| \) and \( |q_2| \) on the two particles.
  - Attractive if the charges are of opposite sign and repulsive if the charges have the same sign.
  - It is a conservative force.

Mathematical formulation for Coulomb’s law is the **electrostatic force** has a magnitude of

\[
F = \frac{k |q_1| |q_2|}{r^2}
\]

\( k = \frac{1}{4\pi\varepsilon_0} = 8.99 \times 10^9 \text{ N m}^2/\text{C}^2 \)

\( \varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N m}^2 \)

\( \varepsilon_0 \) is permittivity of free space

- Electrostatic force is a force has a magnitude and direction

\[
\vec{F}_{12} = \vec{F}_{21}
\]

Charges have same sign → repulsive force

Charges have different sign → attractive force

\[
\vec{F}_{12} = k \frac{q_1 q_2}{r^2} \hat{r}
\]

Always draw the force vector with the tail on the particle.

Fig 21.6 Two charged particles repel each other if they have the same sign of charge, either (a) both positive or (b) both negative. (c) They attract each other if they have opposite signs of charge.
21.4 Coulomb's Law

Coulomb's law like Newton's law of gravity \( F = \frac{Gm_1m_2}{r^2} \)
- Both are ***Field*** forces (no direct contact between charges)
- both are inverse-square laws \( \left( \frac{F}{r^2} \right) \)
- But \( F_g \gg F_e \) between charged particles \( \Rightarrow F_g \) can be neglected
- Ex: in hydrogen atom, the forces ration between an electron and the proton separated by \( 5.3 \times 10^{-11} \) m is \( (F_e/F_g \approx 2 \times 10^{39}) \)

\[
F_e = 8.2 \times 10^{-7} \text{N} \quad F_g = 3.6 \times 10^{-47} \text{N}
\]

### Charge and Mass of the Electron, Proton and Neutron.

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<th>Mass (kg)</th>
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<td>-1.60 \times 10^{-19}</td>
<td>9.11 \times 10^{-31}</td>
</tr>
<tr>
<td>Proton</td>
<td>+1.60 \times 10^{-19}</td>
<td>1.67 \times 10^{-27}</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
<td>1.67 \times 10^{-27}</td>
</tr>
</tbody>
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21.4 Coulomb's Law: Shell theorem

- Shell theorems for spherical symmetry:
  1. A spherical shell of uniform charge attracts or repels a charged particle that is outside the shell as if all the shell’s charge were concentrated at its center.
  2. If a charged particle is located inside the spherical shell of uniform charge, there is no net electrostatic force on the particle from the shell.

\[
F_{Qi} = k \frac{Qq}{r^2}
\]

\( Q \) is uniformly distributed on the surface of the conductors forming spherical shell of charges

21.4 Coulomb's Law: Spherical conductor

- For a spherical conductor, if excess charge is placed on that conductor, the excess charge spreads uniformly over the (external) surface; charges repel one another and tend to move apart \( \rightarrow \) charges spread over the available surface until they are uniformly distributed
- That arrangement maximizes the distances between all pairs of the excess distributed charges on spherical surface forms a spherical shell of uniform charge \( \rightarrow \) we can apply shell theorem for spherical conductors charges.
21.4 Coulomb’s Law: Example

(a) Two positively charged particles, \( q_1 = 1.6 \times 10^{-19} \text{ C} \) and \( q_2 = 3.2 \times 10^{-19} \text{ C} \), lies on x-axis with separation between them \( R = 0.02 \text{ m} \). What is the electrostatic force magnitude and direction on particle 1 from particle 2?

The force magnitude from 2 on 1 is

\[
F_{21} = \frac{1}{4\pi\varepsilon_0} \frac{|q_1||q_2|}{R^2} = \frac{(8.99 \times 10^9)(1.60 \times 10^{-19})(3.20 \times 10^{-19})}{(0.0200 \text{ m})^2} = 1.15 \times 10^{-24} \text{ N}, \quad \vec{F}_{21} = -(1.15 \times 10^{-24} \text{ N})\hat{i}
\]

Note: force from 1 on 2 will have same magnitude by but in opposite direction

\[
\vec{F}_{12} = -(\vec{F}_{21}) = -(1.15 \times 10^{-24} \text{ N})\hat{i}
\]

21.4 Coulomb’s Law: Example – continued from previous slide

(b) If a third charged particle \( q_3 = -3.2 \times 10^{-19} \text{ C} \) is placed between the first two particles at a distance \( \frac{1}{3} R \) from particle 1, find the net force on particle 1.

The force of 3 on 1

\[
F_{31} = \frac{1}{4\pi\varepsilon_0} \frac{|q_1||q_3|}{(\frac{1}{3}R)^2} = \frac{(8.99 \times 10^9)(1.60 \times 10^{-19})(3.20 \times 10^{-19})}{((\frac{1}{3})(0.0200 \text{ m}))^2} = 2.05 \times 10^{-24} \text{ N}, \quad \vec{F}_{31} = (2.05 \times 10^{-24} \text{ N})\hat{i}
\]

The net force on particle 1 is

\[
\vec{F}_{\text{net,1}} = \vec{F}_{21} + \vec{F}_{31} = -(1.15 \times 10^{-24} \text{ N})\hat{i} + (2.05 \times 10^{-24} \text{ N})\hat{i} = (9.00 \times 10^{-25} \text{ N})\hat{i}, \quad \text{(Answer)}
\]

21.4 Coulomb’s Law: Example – continued from previous slide

(b) If a third charged particle \( q_3 = 3.2 \times 10^{-19} \text{ C} \) is placed at a distance \( \frac{1}{3} R \) from particle 1 and at angle 60° with x-axis, find the net force on particle 1.

The force of 4 on 1

\[
F_{41} = \frac{1}{4\pi\varepsilon_0} \frac{|q_1||q_4|}{\left(\frac{1}{3}R\right)^2} = \frac{(8.99 \times 10^9)(1.60 \times 10^{-19})(3.20 \times 10^{-19})}{((\frac{1}{3})(0.0200 \text{ m}))^2} = 2.05 \times 10^{-24} \text{ N}, \quad \vec{F}_{41} = (1.025 \times 10^{-24} \text{ N})\hat{i} + (1.775 \times 10^{-24} \text{ N})\hat{j}
\]

The net force on particle 1 is

\[
\vec{F}_{\text{net,1}} = \vec{F}_{21} + \vec{F}_{31} + \vec{F}_{41} = -(1.15 \times 10^{-24} \text{ N})\hat{i} + (1.025 \times 10^{-24} \text{ N})\hat{i} + (1.775 \times 10^{-24} \text{ N})\hat{j} = (-1.25 \times 10^{-24} \text{ N})\hat{i} + (1.80 \times 10^{-24} \text{ N})\hat{j}
\]

21.4 Coulomb’s Law: Example

Ex: Three point charges lie along the x axis as shown. The positive charge \( q_1 = 15 \mu \text{ C} \) is at \( x = 2 \text{ m} \), the positive charge \( q_2 = 6 \mu \text{ C} \) is at the origin, and the net force acting on \( q_3 \) is zero (\( q_3 \) is at equilibrium). What is the x coordinate of \( q_3 \)?

\[
\vec{F}_3 = \vec{F}_{23} + \vec{F}_{13} = -k \frac{|q_1||q_3|}{x^2} \hat{i} + k \frac{|q_2||q_3|}{(2.00 - x)^2} \hat{i} = 0
\]

\[
(2 - x)^2|q_2| = x^2|q_1|
\]

\[
(4 - 4x + x^2)(6 \times 10^{-16} \text{ C}) = x^2(15 \times 10^{-6} \text{ C})
\]

\[
2x^2 + 8x - 8 = 0 \quad x = 0.775 \text{ m}
\]

Notes: 1- equilibrium is always between similar charges, 2- equilibrium is not between different charges and near the small one
21.4 Coulomb's Law: Example

Two conducting spheres A and B with charge initially shown (a)

Ex: Consider three point charges located at the corners of a right triangle as shown in where \( q_1 = q_3 = 5 \text{ } \mu \text{C}, q_2 = -2 \text{ } \mu \text{C}, \) and \( a = 0.1 \text{ m}. \) Find the resultant force exerted on \( q_3. \)

\[
\vec{F}_{13} = \vec{F}_{13} \cos 45^\circ \hat{i} + \vec{F}_{23} \sin 45^\circ \hat{j}
\]

\[
= 7.9 \hat{i} + 7.9 \hat{j}
\]

Hence, \( \vec{F}_{13} = \vec{F}_{13} + \vec{F}_{23} = -1.1 \hat{i} + 7.9 \hat{j} \)

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21.4 Coulomb's Law: Example – continued from previous

\[ F_{23} = k_e \frac{|q_2||q_3|}{a^2} (\frac{2}{9} \times 10^{-6}) \frac{0 \times 10^{-6}}{(0.1 \text{ m})^2} = 9 \text{ N} \]

\[
\vec{F}_{23} = F_{23} \cos 180^\circ \hat{i} + F_{23} \sin 180^\circ \hat{j}
\]

\[
\vec{F}_{23} = -9 \hat{i}
\]

\[
F_{13} = k_e \frac{(\sqrt{2}a)^2}{(\sqrt{2}a)^2} \frac{5 \times 10^{-6} \times 5 \times 10^{-6}}{2(0.1 \text{ m})^2}
\]

\[ = 11 \text{ N} \]

\[
\vec{F}_{13} = F_{13} \cos 45^\circ \hat{i} + F_{23} \sin 45^\circ \hat{j}
\]

\[
= -2 \mu \text{C} \quad q_1 \quad q_3 \quad 5 \mu \text{C}
\]

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21.4 Coulomb's Law: Example

Ex: Two identical small charged spheres, each having a mass of \( 3 \times 10^{-2} \text{ kg,} \) hang in equilibrium as shown. The length of each string is 0.15 m, and the angle \( \theta \) is 5°. Find the magnitude of the charge on each sphere.

[Free body diagram for left sphere is shown]

\[
\sum F_y = T \sin \theta - F_y = 0 \quad \Rightarrow \quad T \sin \theta = F_y
\]

\[
\sum F_x = T \cos \theta - mg = 0 \quad \Rightarrow \quad T \cos \theta = mg
\]
21.4 Coulomb's Law: Example – continued from previous slide

\[ \tan \theta = \frac{F_x}{mg} \rightarrow F_x = mg \tan \theta \]

\[ F_x = (3 \times 10^{-2} \text{ kg})(9.8 \text{ m/s}^2) \tan 5^\circ = 2.6 \times 10^{-2} \text{ N} \]

But \( F_x = k \frac{|q|^2}{r^2} \) and \( r = 2a \)

\[ \sin \theta = \frac{a}{L} \rightarrow a = L \sin \theta \]

\[ a = (0.15 \text{ m}) \sin 5^\circ = 0.013 \text{ m} \]

\[ F_x = k \frac{|q|^2}{r^2} \rightarrow |q| = \sqrt{\frac{F_x r^2}{k}} = \sqrt{\frac{F_x (2a)^2}{k}} \]

\[ |q| = \sqrt{\frac{(2.6 \times 10^{-2} \text{ N})(2(0.013 \text{ m}))^2}{8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2}} = 4.4 \times 10^{-8} \text{ C} \]

Summary

- Charges can be negative or positive.
- Charge is discrete, conserved.
- Like charges repel, opposites attract.
- Types of materials: Insulators, Semiconductors, conductors
- Electrostatic force obeys Coulomb’s Law.