Today’s Topics

- Electric Force and Electric Fields
  - Electric Charges and Electric Forces
  - Coulomb’s Law
  - Physical Field
  - The Electric Field
  - Electric Field Lines
- Motion of Charged Particle in Electric Field

A Reminder

Lectures supplement but do not substitute for reading!

Lecture Effectiveness = Preview + Lectures + Review

Properties of Electric Charges

- 2+1 types: positive, negative (+neutral).
- Unit: Coulomb (C). 1 C = charge of $6.24 \times 10^{18}$ protons.
- Electric charge is quantized: $q = \pm Ne, \ e = 1.602 \times 10^{-19}$ C
- Building blocks of matters:

<table>
<thead>
<tr>
<th>Charge (C)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$-1.602 \times 10^{-19}$</td>
</tr>
<tr>
<td>Proton</td>
<td>$+1.602 \times 10^{-19}$</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
</tr>
</tbody>
</table>

- Electric charge is conserved: charges can be moved around, but the total charge remains the same.
- For deep thinkers: Why electrons and protons have the same electric charge?

Electric Force And Coulomb’s Law

- Electric forces exist between two charged particles
- The direction of electric force depends on the signs of the charges:
  - forces between opposite sign charges are attractive
  - forces between like sign charges are repulsive
- The magnitude of the electric forces for point charges
  \[ F_{ij} = \frac{kq_i q_j}{r_{ij}^2} \]
  (Coulomb’s Law)

  Coulomb Constant: \( k_c = 8.987 \times 10^9 \text{Nm}^2/\text{C}^2 = 1/(4\pi\varepsilon_0) \)

  \( \varepsilon_0 \): permittivity of free space
Numeric Examples: Electric Force Is Huge

- Electric force between two 1C charges 1 meter apart: 
  \[ F = 8.99 \times 10^9 \text{N} \]
- Proton and electron in a hydrogen atom:
  \[ q_{\text{electron}} = -1.6 \times 10^{-19} \text{C}, \quad q_{\text{proton}} = 1.6 \times 10^{-19} \text{C}, \quad r = 5.3 \times 10^{-11} \text{m} \]
  \[ F = 8.2 \times 10^{-8} \text{N} \]
- This force is huge:
  - Compared to the mass of proton: \( 1.673 \times 10^{-27} \text{kg} \)
  - Compared to the gravitational forces between them:
    \[ F_G = 3.6 \times 10^{-47} \text{N} \] (recall: \( F_G = Gm_1m_2/r^2 \))

- Four fundamental forces:
  Strong > Electromagnetic > Weak >> Gravitational

Coulomb’s Law in Vector Form

- Electric force on \( q_1 \) by \( q_2 \): 
  \[ \vec{F}_{12} = k \frac{q_1 q_2}{r_{12}^2} \]
- Electric force on \( q_3 \) by \( q_1 \): 
  \[ \vec{F}_{31} = k \frac{q_3 q_1}{r_{31}^2} = -\vec{F}_{12} \]

**Exercise:**
Electric Forces Due to Two Charged Particles

- Find the electric force on \( q_3 \).

Solution: See board.

Properties of the Electric Force

- It is one of four fundamental forces:
  Strong > Electromagnetic > weak >> gravity
- It is proportional to \( 1/r^2 \): double \( r \) \( \rightarrow \) \( 1/4 \) \( F \)
- Its direction is charge sign dependent:
  - like sign \( \rightarrow \) repulsive, opposite sign \( \rightarrow \) attractive
- It is a conservative force. (Work independent of path)

\[
W = \int_{r_1}^{r_2} \vec{F} \cdot d\vec{r} = -\frac{k q_1 q_2}{r_1} + \frac{k q_1 q_2}{r_2} = (-U_f) - (-U_i)
\]

- A potential energy can be defined. (Ch. 25)

\[
U = \frac{k q_1 q_2}{r}
\]
A Very Important Concept: Field

What is a “field”?  

Field: A physical quantity which has a physical value at each point in space (i.e. a distribution).

Examples of physical fields: temperature, wind speed, electric field, magnetic field, …

In this course, we consider only scalar and vector physical quantities.

Example of Scalar and Vector Fields

Temperature (scalar)  Wind speed (vector)

Measurement can be made at any point on the map.

The Coulomb’s Law Revisited

Original (Coulomb’s) view of electric force:  
$q_1$ directly applies an electric force on $q_2$

$\vec{F}_{12} = \frac{q_1 q_2}{r_{12}^2} \hat{r}_{12}$

“Modern” view of electric force:  
• $q_1$ creates an electric field $\vec{E}$ around it  
• The electric field $\vec{E}$ applies a force on $q_2$

$\vec{F}_s = K_e \frac{q_1 q_2}{r_{12}^2} \hat{r}_{12}$  $q_1 = \vec{E} q_2$

In this modern view:
$q_1$: source charge  
$q_2$: test charge  
$\vec{E}$ independent of $q_2$!

Electric Field and Electric Force

$q_s$: source charge  
$\vec{E}$: field by $q_s$  
$q$: test charge  
$\vec{F} = q \vec{E}$ force on $q$ by $\vec{E}$
Visualization of Electric Field: Field Lines

- Use of field lines is a convenient way to visualize electric fields
- Simple rules for drawing field lines:
  - line direction: direction of E vector
  - line density: relative strength of E. (denser = larger)

Field Lines e.g.: Point-Like Charges

- Magnitude $E = k_e q/r^2$

Example 2: Two Charged Particles

- Each field line always starts from a +q and end at a -q (or infinity)

Motion Of Charged Particle in The Electric Field

- Fundamental Formulas:
  - $F = qE$
  - $a = F/m = qE/m$
  - $v = v_i + at$

- If initially rest ($v_i = 0$), then $v = at = (qE/m)t$
- Motion of +q: Same dir. as $E$
- Motion of - q: Opposite dir. as $E$
Exercise: An Electron in a Uniform E. Field

- Find out vertical displacement after the electron pass through a downward uniform electric field $E$
- Solution: Exercise with your TAs
  Answer: $dy = -\frac{1}{2} \left(\frac{e}{m}\right)E \left(\frac{l}{v_i}\right)^2$