Chapter 6

Electricity (& Magnetism)

Introduction

- First five chapters were "Newtonian Physics", mechanical explanations based on Newton's Laws applied to motion of particles.
- In the early 1800's, science tried to extend mechanical models to electricity, magnetism, and light, but were unsuccessful.
- Now we successfully use **Field Models**, which examine how objects modify the space around them.
- This chapter discusses two fields: Electric and Magnetic.
- Electricity & Magnetism are strongly interrelated.

(Electric) Charge

Electric Charge Discovery (Ben Franklin & Volta)

- Basic property related to ability to interact with an Electric Force.
- {DEMO} Early (1750–70) experiments proved: **two kinds of charge**.
- Like charges repel, opposites attract. (Ben Franklin & Volta)
- To help calculations, charges are named **positive** and **negative**.
  - The assignment of which acted positive and which acted negative was unfortunately made before we knew the **TRUE origin** of these charges.

Electron Theory of Charge (1890s)

Electric Charges (& Forces)

- ALL Charges come from the parts of atoms called: **Protons** $\langle + \rangle$ and **Electrons**. $\langle - \rangle$ (See **Fig.6.2**.)
    - Atoms also have neutral **Neutrons**.
    - Proton & Electron Charges have the **same magnitude** (later slide), **called the Basic Charge**.
- **Net Charge** $= \left(\textbf{Num. of Protons} - \textbf{Num. of Electrons}\right) \times \textbf{Basic Charge}$.
    - Most objects have the same number of each, and are uncharged. (They show NO **Electric** attraction.)
- In drawings we use a few **+** or **–** signs to indicate charge on object.
- Protons stay put, electrons move around.
    - Most atoms are electrically neutral. But we define:
        - **Positive Ion**: Somehow **lost** electron(s).
        - **Negative Ion**: Somehow **gained** electron(s).

    (See Fig.6.3, p.153)

Electrostatic Charge

- Recall that most objects are initially **uncharged** (have **NO** net charge).
- However, **Electrons can** be moved from one object to another.
  - (Franklin's early theory said both charges moved.)
- The **RESULT** is an "**electrostatic NET charge**" that the object keeps.
- **Methods of Charging**:
  - Friction:
    - Rubbing one object over another **Adds or Removes Electrons**.
  - Contact: { BOARD }
    - Touching an already **charged** object to another.
  - Induction: { BOARD }
    - Occurs without touching.
    - Nearby charged object separates **+ & –** charges in other object.
    - Not really a transfer of charges.
    - Process is **reversible**.

Electrical Conductors and Insulators

- **Conductor**: Charge flows through it **VERY** easily. Metals, moisture, human bodies, and a few others.

  In Conductors, the ELECTRONS ARE FREE TO MOVE.

- **Insulator**: All other materials **resist** the flow of charge.
- **Grounding**: { BOARD } Placing an object in electrical contact with the Earth. Grounded objects lose charge to the Earth.

Measuring Electrical Charges

- **Symbol for Charge**: **q**   Unit: Coulomb [C].
- Coulomb is very large. Typical charge on object is about 10^{-6} **C [μC].**
- Experimentally Discovered Fact: { ABOUT 1910 }
  Objects do not charge in a continuous fashion { DRAW }. Therefore:
- Charged objects **MUST** have **INTEGER multiples** of some basic charge.

- **Basic Charge:** $\textbf{Proton} = +1.60\times10^{-19}\ \textbf{C}$; $\textbf{Electron} = -1.60\times10^{-19}\ \textbf{C}$
- **(Net) Charge on obj. =** $(\textbf{Num. of Prot} - \textbf{Num. of Elect}) \times \textbf{Basic Charge}$.

Measuring Electrical Forces

- **Coulomb's Law**: $$\mathbf{F_e} = \frac{\mathbf{k}\,\mathbf{q}_1\mathbf{q}_2}{\mathbf{d}^2}$$
  - Where $\mathbf{q_1}$, $\mathbf{q_2}$ are charges on objects 1 and 2, separated a distance **d**, and $\mathbf{k} = 9.00\times10^{9}\,\mathbf{N\cdot m^2/C}^2$.
  - **Action at a distance force**, like gravitational force.
  - There are similarities between electric and gravitational forces.
  - But there are also differences. The biggest are:
    - **Electric** Forces can be much, **much stronger**.
    - Electric Forces can be attractive or repulsive.

Force Fields

- **Contact forces** are applied directly by obvious physical links,
- **Action at a distance forces** seem to appear mysteriously.
  - Physicists found that a new idea, called the (Force) **Field Model**, helped them draw, and make calculations on, these kinds of forces.
  - First success was with the **Electric Force**, and later extended to Magnetic (and Gravitational) Forces.
    - We **assume** that electrically charged objects somehow modify the space around them to create an **electric (force) field**.
    - Other charged objects brought near the original objects, react to this field.

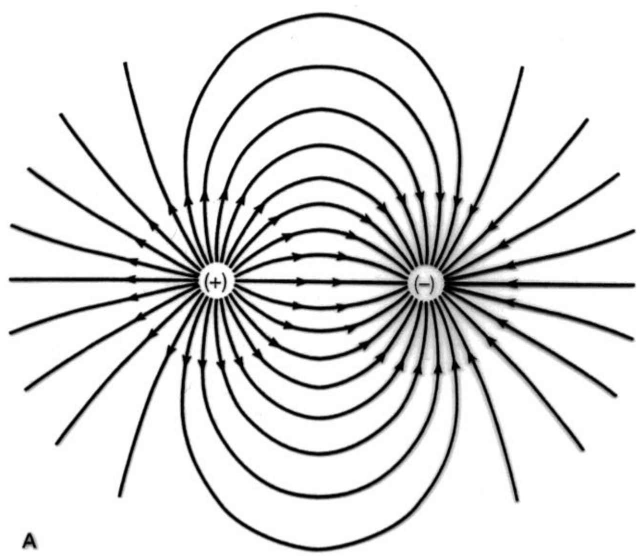
Drawing an Electric Field:

- **DEMO** Start with 1 positive (+) charge:
  - We draw the field as lines with arrows.
  - Arrows show the direction a small positive **test** charge moves in the field created around the original charge.

Drawing an Electric Field: (Continued)

- **DEMO** Add 1 negative (-) charge: **Fig.6.7.A, p.157**.
  - The field lines start and/or end on the charges.
  - Arrows point from **plus** to **minus** everywhere.
  - Field lines never cross since at each point in the field, the test charge can move in only one direction.
  - Closer line spacing represents stronger electric forces.

(**Coulomb's Law:** $\mathbf{F_e} = \dfrac{\mathbf{k\,q_1 q_2}}{\mathbf{d}^2}$)



Electric Potential

- { DRAW} To move charged object against **(electric)** force, you do work.
- Work done (W) on charge = increase in Electric Potential Energy .
- A more useful concept is **work done per unit charge**. This is the **Electric Potential**, which depends only on the Electric Field**.**
- Electric Potential is often also called the **potential difference** **PD** (between two points in field).

- **Potential Diff. Def:** $\mathbf{PD = \frac{W}{q}}$ **[volts, V]** $\left\{ \mathbf{1\ V = 1 \frac{J}{C}} \right\}$
  - We'll use this concept in describing how charges flow around circuits.

Electric Current

- Now we'll talk about Moving Charges, or **(Electric) Currents**.

- **Current Definition:** $\mathbf{I = \frac{q}{t}}$ **[Ampere, A]** $\left\{ \mathbf{1\ A = 1\frac{C}{s}} \right\}$

- **Do** **Ex. B-5, p.190.**
  SHOULD READ: What is the magnitude of the least possible **NON-ZERO** current that could flow in ONE SECOND.

The Electric Circuit

- A **conducting path** through which current can flow.
- The path is **closed** ("circuit" means "closed path").
- Circuits must contain:
  - An **Energy source** to give electrons higher Electric Potential. **PD [V]**
    - **Voltage Source**: common name for energy source.
  - An **Energy sink** where electrons do work and thus lose energy.
    - **Voltage Drop**: common name for energy sink.
- **In a circuit**: **Experiments** show: $\mathbf{I} \propto \mathbf{PD}$.

- **Voltage** $\boldsymbol{V}$: COMMON name for potential difference in circuits.
- $\therefore$ **In a circuit**: $\mathbf{I} \propto \mathbf{V}$.

<u>The Nature of Current</u>

- {DRAW conductor} With no voltage, the free electrons in a conductor constantly move in a **random** fashion. The **NET MOTION is ZERO.**
- <u>Voltage sources have **+** and **– CHARGED** terminals</u>.
  - The **charges create an electric field in** the **conductor**.
    - (Experiments show the Field is not set up instantly along the whole conductor. It "travels" at about the speed of light, ≈ 1 ft/ns.)
  - This Field adds a **SLOW "<u>drift velocity</u>"** towards the **+** terminal.
- **<u>Electron Current</u>**: is the **direction electrons actually drift. (From – to +.)**
- **<u>Conventional Current</u>**: Ben Franklin assumed that both positive and negative charges flow. The "**conventional" current direction** is the direction **positive charges would drift**. (From **+** to **–**.)
- Either current can be used in problems. **<u>Most</u> use Conventional.**

Two Types of Current

- **Direct Current ("dc"):** { DRAW }
  - The + and - terminals of the voltage source stay the same.
  - Electrons always drift in one direction.
  - Batteries and solar cells produce **dc**.
- **Alternating Current ("ac"):** { DRAW }
  - The + and - terminals of the voltage source switch back and forth many times per second.
  - Electrons drift one direction and then the other.
  - Electric utilities produce **ac** for use in industry and homes.
    (Why they make AC is on the next to last slide)

Electrical Resistance

- Recall, experiments showed that in a circuit: $\mathbf{I \propto V}$.
- **Electrical resistance** is the property that measures how difficult it is for a PD to get current to flow.
- **Experiments also show**: Smaller resistance, larger current for fixed $\boldsymbol{V}$.

- **These 2 Experiments Together Show**: $\mathbf{I \propto \frac{V}{R}}$

- **Resistance Def**: $\mathbf{R = \frac{V}{I}}$

  - Unit: Ohm [Ω] $\mathbf{1\,\Omega = 1\frac{V}{A}}$ (m-k-s definition)

    - (Extra Info Used Later: For a given wire, $\mathbf{R \propto \frac{Length}{x.s.Area}}$.)

- **Ohm's Law**: $\mathbf{V = IR}$

Electrical Power and Electrical Work

- From the definitions of electric potential, power, and current we can derive the:

- **Power Eqn:** $\mathbf{P = IV}$

- **Do Ex. B-8, p.191.**

- Electric Utility Meters:
  - These meters measure $\mathbf{P \times t} = \text{Work Done} = \text{Energy Supplied.}$
  - The meter's unit is kW-hr. = 3,600,000 J.

- **Electricity Cost Eqn:** $\text{Cost [\$]} = \text{Rate [\$/kW.hr]} \times \text{Power [kW]} \times \text{time on [hr]}$

<u>Magnetism</u> [Reading Assignment = Perm. Magnets & Earth's Magnetism]

<u>Magnetic Poles</u>

- **Experiments** with magnets show that: { DEMO }
  - Each end of a magnet attracts one end and repels the other end of another magnet.
  - The two ends act like the two kinds of charge.
  - The ends are called <u>**magnetic poles**</u>.
  - <u>**Like poles repel, unlike poles attract.**</u>
  - We name them <u>**North**</u> and <u>**South**</u>,
    - **N** <u>points</u> in the approximate <u>direction NORTH</u> on <u>Earth</u>.
  - **The poles always appear in pairs called <u>dipoles</u>.**
    - Because the source of <u>**ALL**</u> magnets' magnetism is from <u>**electron current**</u> loops in their individual atoms (to be discussed later),

      <u>They cannot be broken into magnetic **monopoles**.</u>

<u>Magnetic Fields</u>

- We imagine that the poles modify the space around them to create a <u>**magnetic field**</u>, <u>then OTHER magnets react to this field</u>.
- We draw the field as lines with arrows. **Fig.6.20, p.168**.
- The arrows show the direction a **compass N-pole** would point.
- Field lines never cross.
- Closer line spacing represents stronger magnetic forces.
- Lines run **N** to **S** outside magnet and return **S** to **N** inside.

<u>The Source of Magnetic Fields</u>

- Oersted discovered <u>experimentally</u> in 1820 that **any moving charge creates a magnetic field** (remember, <u>moving charge = current</u>).
- We now believe **all magnetic fields** (even those around a magnet) are **created by moving charges** as described in next section.
- <u>**Permanent Magnets**</u>: Reading Assignment.
- <u>**Earth's Magnetic Field**</u>: Reading Assignment. Earth's field comes from electric currents created by Earth's rotation.

Electric Currents and Magnetism

- **Fig.6.23, p.160** shows how Oersted accidentally found that currents create magnetic fields.
- He later did a better experiment:

- DEMO Show: **Oersted's Better Experiment: (Fig.6-25)**
  - Vertical wire running through a horizontal table.
  - With Zero **current** in the wire,
    - Compass needles everywhere will point **North**.
  - With **Electron Current** flowing **UP**,
    - Compass needles everywhere will point **CW** around the wire.
  - Reverse the current,
    - all needles will point **CCW**.
  - Field **direction** is given by "**Left Hand Rule**" (for wires).

Current Loops

- Here's how currents make magnets:

- **DEMO** Show: (**Fig.6.26)**
  - Loop of wire, with **Electron** **Current** flowing **CW** around it.
    - **Inside** loop, a compass needle will always point **UP**.
    - **Outside** loop, it will always point **DOWN**.
      - Reverse the current, and the magnetic field reverses.
    - ("**Left hand rule**" (for loops) gives the Field **direction inside**.
- Note that fields are **similar** to **Bar Magnet's**:

Atomic Dipoles:

- All magnetism is caused by the electrical currents generated by
  - electrons orbiting around the nucleus of the atom and
  - electrons spinning on their own axis (like spinning tops).
- That's why you can't break a big magnet into a monopole — Each atom is its own little **atomic dipole magnet**.
- The atoms of most materials are non-magnetic.
  - The orbits and spins of their electrons are oriented so that the magnetic fields tend to cancel each other.
- Only the few "**ferromagnetic**" materials have magnetic atoms.

Applications of Electromagnets

- **Solenoid: (See Fig.6.27, p.171).**
  - Many loops of wire formed into a cylinder.
  - **Inside** cylinder, **fields** from each loop **add** for **stronger field**.
- **Electromagnet:**
  - Magnet made from a solenoid.
  - **Field strength varies** with the current in the solenoid.

Electric Meters (See Fig.6.28, p.172).

- The "**Galvanometer**" is the basic electric meter.
  ALL Analog Electric Meters use a Galvanometer to measure current.
  - Blue is a spring that keeps the pointer at 0 with no current.
  - The Solenoid is the small gray part. Its **axis** should be shown **parallel to the red pointer**.
- Current in solenoid creates field parallel to pointer.
- Pointer rotates against the restoring force of the spring.
- Rotation amount varies with current.

Electromagnetic Switches (Relays) (See Fig.6.29, p.173).

- Low current in solenoid creates magnetic field, which attracts the iron part of a switch contact.
- Contact can control a much larger voltage or current.

Telephones and Loudspeakers (See Fig.6.30, p.174)

- The **Loudspeaker** is the electromagnetic part.
  - Audio Frequency current in an electromagnet creates a varying magnetic field, making it vibrate in the permanent magnet's field.
  - This vibrating electromagnet is attached to the base of the speaker cone; thus the whole cone vibrates and **emits a sound wave**.

Electric Motors (See Fig.6.31, p.174)

- Very much like the galvanometer, but:
  - no springs that would keep the solenoid centered,
  - added "**commutator**" to change current direction in solenoid each half revolution.
  - External field is usually supplied by an **electromagnet, as shown**.

Electromagnetic Induction

- Scientific question: since electric currents produce magnetic fields, might magnetic fields produce currents?

Induction Discovery (1831)

- Experiments in both US and England similar to **Fig.6.32** (p.165).
  - Current direction reverses along with the magnet's motion.
  - Same effect with either coil or magnet moving.
  - Current magnitude is proportional to:
    - Number of wire loops.
    - Strength of magnetic field.
    - Speed of magnet motion relative to wires (unexpected).

Generators

- Generator construction is similar to motor, **Fig.6.31** (RE-SHOW).
  - but Uses a mechanical power source to rotate the Armature axle.
  - **Fig.6.33:** A.C. generators use brushes & **NO** commutator.
    - Current alternates + and – (at 60 Hz in the US).
    - (Power Company AC generators use 3 armatures spaced 120° apart & 4 brushes.)
  - **DEMO:** D.C. generators use brushes & must also **have** a commutator.
    - Current varies, but stays +.
    - The gap in the commutator ring wears out the brushes much more rapidly than in the A.C. Generator.

Transformers

- Uses electromagnetic induction to change AC voltage.
- A simple construction geometry is shown in **Fig.6.34** (DEMO).
  - **P**rimary AC current makes Alternating magnetic field in iron ring.
  - Alternating magnetic field **induces** current in **s**econdary.
  - **Voltage ratio**: $\frac{\mathbf{V_p}}{\mathbf{V_s}} = \frac{\mathbf{N_p}}{\mathbf{N_s}}$. Going to **more** turns, *V* steps **up**.
  - **Transformer energy conservation**: $\begin{array}{c}\textbf{Power In} = \textbf{Power Out} \\ \mathbf{I_p V_p = I_s V_s}\end{array}$.
  - **Current ratio**: $\frac{\mathbf{I_p}}{\mathbf{I_s}} = \frac{\mathbf{N_s}}{\mathbf{N_p}}$. Going to **more** turns, *I* steps **down**.

- Do Ex. B-16, p.191.

<u>Commercial Power Transmission</u> **(See "Current War" top of p.176)**

- Homes today have a capacity to use up to 24,000 W at 240 V, which requires a current supply of 100 A.
- Power loss due to a wire's resistance: $\mathbf{Power\ \ Loss = I^2R}$
  - Recall: $\mathbf{R \propto \frac{Length}{Diameter^2}}$, where **Length** is the distance power must be transmitted.
  - The fattest wire available for transmitting 100 A loses too much power when $\mathbf{I}^2 = 10{,}000\ \mathbf{A}^2$.
- **<u>Solution</u>**: after generator, step up to **High V, Low I** for transmission.
  - <u>Example</u>: boosting to 240,000 **V** drops I to 0.1 A and $\mathbf{I}^2$ **to** 0.01 $\mathbf{A}^2$.
- Before entering house, step down to **240 V, 100 A** to supply power being used in house.

Producing Radio Waves (Preview of next chapter.)

Maxwell's Electromagnetic Wave Theory (1865) (Theorist)

- **Suggested Theoretically That**:
  - •• { BOARD } **Electromagnetic Waves**: In an antenna, vibrating electrons produce a **spreading** wave of **varying magnetic field** that, in turn, **creates** a **varying electric field**.
  - ••Energy is carried by these varying E and M fields, **which can exist in ANY material AND in a vacuum.**

Heinrich Hertz (1887) (Experimentalist)

- Used **Maxwell's suggestions** to
  - Produce,
  - Transmit over a Significant Distance, and
  - Detect these "Radio" Waves.