Physics Notes (Electricity and Magnetism)

Table of Contents

1. Electromagnetic Waves 1.1 Introduction 1.2 Types of radiation 1.3 Uses of electromagnetic waves 1.4 Summary
2. Gravitational Field 2.1 Concept of gravitational field 2.2 Gravitational force between two masses 2.3 Relation between 'G' and 'g' 2.4 Gravitational potential 2.5 Kepler's laws 2.6 Natural and artificial satellites 2.7 Escape velocity 2.8 Summary
3. Electric Field I 3.1 Electric force between point charges: Coulomb's law 3.2 Electric field intensity 3.3 Electric potential 3.4 Capacitors and capacitances 3.5 Energy stored in a capacitor 3.6 Summary
4. Electric Field II: Current Electricity 4.1 Production of continuous charges 4.2 Arrangement of cells and resistors 4.3 Resistivity and conductivity 4.4 Galvanometer conversions 4.5 Principle of a potentiometer 4.6 Measurement of resistance by ammeter-voltmeter method 4.7 Summary
5. Electric Field III: Conduction through Liquids and Gases 5.1 Conduction through liquids: electrolysis 5.2 Dynamics of charged particles in electrolytes 5.3 Examples of electrolysis 5.4 Applications of electrolysis 5.5 Faraday's law of electrolysis 5.6 Conduction of electricity through gases 5.7 Hot cathode: Thermionic emission 5.8 Summary
6. Magnetic Field 6.1 Concept of magnetic field 6.2 Patterns of magnetic field 6.3 Methods of making magnets 6.4 Electromagnets and their application of electromagnetic field 6.5 The earth's magnetic field 6.6 Magnetic force on a charge moving in a magnetic field 6.7 Summary

1. Electromagnetic Waves

1.1 Introduction

- **Definition:** Electromagnetic (EM) waves are waves that are created as a result of vibrations between an electric field and a magnetic field. They do not require a medium for propagation and can travel through a vacuum.
- **Speed:** All electromagnetic waves travel at the speed of light in a vacuum ($c \approx 3 \times 10^8$ m/s).
- **Nature:** They are transverse waves, meaning the oscillations of the electric and magnetic fields are perpendicular to each other and to the direction of wave propagation.

1.2 Types of Radiation (Electromagnetic Spectrum)

- The EM spectrum is a continuous range of all possible electromagnetic waves, arranged by frequency or wavelength.
- From longest wavelength/lowest frequency to shortest wavelength/highest frequency:

- **Radio Waves:** Longest wavelengths, lowest frequencies. Used in broadcasting, communication, remote control.
- **Microwaves:** Shorter than radio waves. Used in cooking (microwave ovens), radar, satellite communication, Wi-Fi.
- **Infrared Radiation (IR):** Heat radiation. Used in remote controls, thermal imaging, night vision, optical fibers.
- **Visible Light:** The only part of the spectrum visible to the human eye (ROYGBIV). Used for sight, illumination.
- **Ultraviolet Radiation (UV):** Shorter than visible light. Causes sunburn, used in sterilization, tanning beds.
- **X-rays:** High energy, penetrating. Used in medical imaging (bone fractures), security scans.
- **Gamma Rays (γ-rays):** Highest energy, shortest wavelengths. Produced by radioactive decay, used in cancer therapy, sterilization of medical equipment.

1.3 Uses of Electromagnetic Waves

- **Radio Waves:** Radio and TV broadcasting, mobile phones, satellite communication, MRI.
- **Microwaves:** Microwave ovens, radar speed guns, satellite television, GPS.
- **Infrared:** Remote controls, fiber optics, night vision goggles, thermal cameras, heating.
- **Visible Light:** Illumination, photography, optical microscopes, fiber optics.
- **Ultraviolet:** Sterilization, detecting forged banknotes, sunbeds.
- **X-rays:** Medical imaging (radiography), airport security scanners, material analysis.
- **Gamma Rays:** Radiotherapy for cancer, sterilization of food and medical instruments.

1.4 Summary

- EM waves are transverse waves of oscillating electric and magnetic fields, traveling at the speed of light in vacuum.
- The electromagnetic spectrum covers a wide range of waves from radio to gamma rays, each with distinct wavelengths, frequencies, and applications.

2. Gravitational Field

2.1 Concept of Gravitational Field

- **Definition:** A region of space around a mass where another mass would experience a gravitational force. It is a field force, meaning objects do not need to be in contact to experience the force.
- **Gravitational Field Strength (g):** The gravitational force per unit mass at a point in the gravitational field.

- **Formula:** $g = \frac{F}{m}$
- **Unit:** Newtons per kilogram (N/kg) or metres per second squared (m/s²). Near Earth's surface, $g \approx 9.8\ \text{N/kg}$ or $9.8\ \text{m/s}^2$.

2.2 Gravitational Force Between Two Masses (Newton's Law of Universal Gravitation)

- **Principle:** Every particle in the Universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

- **Formula:** $F = \frac{Gm_1m_2}{r^2}$
- **G:** Universal Gravitational Constant ($6.67 \times 10^{-11}\ \text{N m}^2\ \text{kg}^{-2}$).
- m_1, m_2: masses of the two objects.
- r: distance between their centers.

2.3 Relation between 'G' and 'g'

- We know that the weight of an object on Earth is $W = mg$.
- Also, the gravitational force on an object of mass m due to Earth (mass M_E, radius R_E) is $F = \frac{GM_E m}{R_E^2}$.
- Equating these: $mg = \frac{GM_E m}{R_E^2}$
- Therefore, $g = \frac{GM_E}{R_E^2}$
- This shows that 'g' depends on the mass and radius of the planet.

2.4 Gravitational Potential

- **Definition:** The work done per unit mass in bringing a small test mass from infinity to a point in the gravitational field without acceleration.
- **Formula:** V = GM/r (The negative sign indicates that gravity is an attractive force and work is done *by* the field).
- **Unit:** Joules per kilogram (J/kg).
- Gravitational potential is a scalar quantity.

2.5 Kepler's Laws

- **Kepler's First Law (Law of Orbits):** All planets move in elliptical orbits with the Sun at one of the two foci.
- **Kepler's Second Law (Law of Areas):** A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time. This implies planets move faster when closer to the Sun.
- **Kepler's Third Law (Law of Periods):** The square of the orbital period (T) of a planet is directly proportional to the cube of the semi-major axis (r) of its orbit.

- Formula: $T^2 \propto r^3$ or $\frac{T^2}{r^3} = \text{constant}$

2.6 Natural and Artificial Satellites

- **Satellite:** An object that orbits another, larger object.
- **Natural Satellites:** Celestial bodies that orbit planets (e.g., the Moon orbiting Earth).
- **Artificial Satellites:** Man-made objects launched into orbit around Earth or other celestial bodies.
    - **Types of Orbits:**
        - **Low Earth Orbit (LEO):** For communication, Earth observation, weather satellites.
        - **Geostationary Earth Orbit (GEO):** A specific type of GSO where the satellite remains above the same point on the equator. Used for communication and broadcasting.
        - **Polar Orbit:** Passes over both poles, used for mapping and surveillance.
- **Uses of Artificial Satellites:** Communication, weather forecasting, GPS, Earth observation, scientific research, espionage.

2.7 Escape Velocity

- **Definition:** The minimum speed an object needs to completely escape the gravitational pull of a massive body (like a planet or star) and not fall back.

- Formula: $v_{esc} = \sqrt{\frac{2GM}{R}}$
    - For Earth, $v_{esc} \approx 11.2\ \text{km/s}$.

2.8 Summary

- Gravitational field is a region where mass experiences force.
- Newton's Law of Universal Gravitation describes attractive forces between masses.
- 'g' is gravitational field strength, dependent on the planet's mass and radius.
- Gravitational potential is work done per unit mass.
- Kepler's Laws describe planetary motion.
- Satellites orbit celestial bodies with various uses.
- Escape velocity is the minimum speed to leave a gravitational field.

3. Electric Field I

3.1 Electric Force Between Point Charges: Coulomb's Law

- **Coulomb's Law:** The electrostatic force between two point charges is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between their centers.

  - Formula: $F = \frac{kq_1q_2}{r^2}$
  - k: Coulomb's constant $(8.99 \times 10^9\ \mathrm{N\ m^2\ C^{-2}})$ or $k = \frac{1}{4\pi\epsilon_0}$.
  - q_1, q_2: magnitudes of the charges.
  - r: distance between the charges.
  - Nature of Force: Attractive if charges are opposite, repulsive if charges are the same.

3.2 Electric Field Intensity (E)

- **Definition:** The electric force per unit positive test charge at a point in an electric field. It is a vector quantity.
  - **Formula:** E = F/q0 (where q0 is a small positive test charge).
  - **Unit:** Newtons per Coulomb (N/C) or Volts per metre (V/m).
- **Electric Field Lines:** Imaginary lines used to represent an electric field.
  - Originate from positive charges and terminate on negative charges.
  - The density of lines indicates the strength of the field.
  - Lines never cross each other.
  - Tangent to the line at any point gives the direction of the electric field at that point.
- **Field due to a Point Charge:** $E = kq/r^2$

3.3 Electric Potential (V)

- **Definition:** The work done per unit positive test charge in moving it from infinity to a point in an electric field without acceleration. It is a scalar quantity.
    - **Formula:** V = W/q0
    - **Unit:** Volts (V), which is Joules per Coulomb (J/C).

- **Electric Potential Difference (ΔV or pd):**
  The work done per unit charge in moving a charge between two points in an electric field.
    - **Formula:** $\Delta V = V_B - V_A = \frac{W_{AB}}{q_0}$
- **Relationship between E and V:** $E = -\frac{\Delta V}{\Delta x}$
  (Electric field is the negative gradient of electric potential).

3.4 Capacitors and Capacitances

- **Capacitor:** A device that stores electric charge and electrical potential energy. Typically consists of two conductive plates separated by an insulating material (dielectric).
- **Capacitance (C):** A measure of a capacitor's ability to store charge. It is the ratio of the charge stored on one plate to the potential difference across the plates.
    - **Formula:** C = Q/V
    - **Unit:** Farad (F). 1 Farad = 1 Coulomb per Volt. (Farad is a very large unit, so microfarads (μF) and nanofarads (nF) are common).

- Factors Affecting Capacitance of a Parallel Plate Capacitor:
  - Area of plates (A): $C \propto A$
  - Distance between plates (d): $C \propto \frac{1}{d}$
  - Permittivity of the dielectric material (ϵ):

$$C = \frac{\epsilon A}{d} = \frac{\epsilon_r \epsilon_0 A}{d}$$

3.5 Energy Stored in a Capacitor

- When a capacitor is charged, work is done to move charge against the electric field, and this energy is stored in the electric field between the plates.
  - Formula: $E = \frac{1}{2} CV^2 = \frac{1}{2} QV = \frac{Q^2}{2C}$
  - Unit: Joules (J).

3.6 Summary

- Coulomb's Law describes force between charges.
- Electric field intensity is force per unit charge.
- Electric potential is work done per unit charge.
- Capacitors store charge and energy, with capacitance being a measure of this ability.
- Energy stored depends on capacitance and voltage squared.

4. Electric Field II: Current Electricity

4.1 Production of Continuous Charges (Electric Current)

- **Electric Current (I):** The rate of flow of electric charge.
  - **Formula:** I = Q/t
  - **Unit:** Ampere (A). 1 Ampere = 1 Coulomb per second.
- **Conditions for Current Flow:**
  1. Presence of charge carriers (e.g., free electrons in metals, ions in electrolytes).
  2. A potential difference (voltage) across the conductor to drive the charges.

- **Sources of Emf (Electromotive Force):** Devices that provide a potential difference and convert other forms of energy into electrical energy (e.g., batteries, generators, solar cells).

4.2 Arrangement of Cells and Resistors

- **Cells (Batteries):**
  - **Series Connection:** Total EMF adds up (E_total = E1 + E2 + ...). Total internal resistance adds up.
  - **Parallel Connection:** Total EMF is the same as one cell (if identical). Total internal resistance decreases. Used for longer discharge times.
- **Resistors:** Components that oppose the flow of current.
  - **Series Connection:** Total Resistance (R_total) is the sum of individual resistances (R_total = R1 + R2 + ...). Current is the same through each resistor. Voltage divides.
    - **Parallel Connection:** Reciprocal of total resistance is the sum of reciprocals of individual resistances ($\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + ...$). Voltage is the same across each resistor. Current divides.

4.3 Resistivity and Conductivity

- **Resistance (R):** Opposition to current flow. Unit: Ohm (Ω).
  - **Ohm's Law:** V = IR
- **Resistivity (*p*):** An intrinsic property of a material that quantifies how strongly it resists electric current.

    - **Formula:** $R = \rho \frac{L}{A}$ (where L is length, A is cross-sectional area).
    - **Unit:** Ohm-metre (Ω m).
- **Conductivity (σ):** The reciprocal of resistivity, indicating how well a material conducts electricity.
    - **Formula:** $\sigma = \frac{1}{\rho}$
    - **Unit:** Siemens per metre (S/m) or $\Omega^{-1}\ \mathrm{m}^{-1}$.

- **Factors Affecting Resistance:** Length (increases with L), cross-sectional area (decreases with A), material type (resistivity), temperature (usually increases for metals, decreases for semiconductors).

4.4 Galvanometer Conversions

- **Galvanometer:** A sensitive device used to detect small electric currents.
- **Ammeter:** Measures current (connected in series). A galvanometer can be converted to an ammeter by connecting a **low resistance shunt in parallel** with it.
- **Voltmeter:** Measures potential difference (connected in parallel). A galvanometer can be converted to a voltmeter by connecting a **high resistance multiplier in series** with it.

4.5 Principle of a Potentiometer

- **Potentiometer:** A device used for precise measurement of potential difference, comparison of EMFs of cells, and determination of internal resistance of a cell.
- **Principle:** The potential difference across any length of a uniform wire carrying a constant current is directly proportional to that length.
    - $V \propto L$ or $V = kL$ (where k is potential gradient).
- **Advantages:** It draws no current from the circuit when balancing, hence it measures true EMF or PD.

4.6 Measurement of Resistance by Ammeter-Voltmeter Method

- **Method:** Apply a voltage (V) across a resistor and measure the current (I) flowing through it using an ammeter in series and a voltmeter in parallel.
- **Ohm's Law:** Resistance R = V/I.
- **Limitations/Errors:** The ammeter has some resistance (though small), and the voltmeter draws some current (though small), leading to slight inaccuracies.

4.7 Summary

- Current is flow of charge, driven by potential difference.
- Cells and resistors can be arranged in series or parallel, affecting total EMF/resistance.
- Resistivity is an intrinsic property of materials.
- Galvanometers can be converted to ammeters (shunt in parallel) or voltmeters (multiplier in series).
- Potentiometers measure PD accurately without drawing current.
- Resistance can be measured using the ammeter-voltmeter method and Ohm's Law.

5. Electric Field III: Conduction through Liquids and Gases

5.1 Conduction Through Liquids: Electrolysis

- **Electrolysis:** The process of using electrical energy to drive a non-spontaneous chemical reaction.
- **Electrolyte:** A liquid (molten ionic compound or solution of an ionic compound) that conducts electricity due to the presence of free moving ions.
- **Electrodes:** Conductors through which current enters or leaves the electrolyte.
    - **Anode:** Positive electrode (where oxidation occurs, anions move towards it).
    - **Cathode:** Negative electrode (where reduction occurs, cations move towards it).
- **Ions:** Charged particles (cations are positive, anions are negative).

5.2 Dynamics of Charged Particles in Electrolytes

- When a potential difference is applied across electrodes in an electrolyte, the electric field exerts forces on the ions.
- Positive ions (cations) move towards the negative electrode (cathode).
- Negative ions (anions) move towards the positive electrode (anode).
- This directed movement of ions constitutes the electric current in the electrolyte.

5.3 Examples of Electrolysis

- **Electrolysis of Water:** Decomposing water into hydrogen gas at the cathode and oxygen gas at the anode.
- **Electrolysis of Copper(II) Sulphate:** Electroplating with copper, or refining copper.
- **Electrolysis of Molten Sodium Chloride:** Producing sodium metal and chlorine gas.

5.4 Applications of Electrolysis

- **Electroplating:** Coating one metal with a thin layer of another metal (e.g., chrome plating, silver plating) for protection or aesthetics.
- **Electrorefining:** Purifying metals (e.g., copper refining).
- **Electrometallurgy:** Extracting reactive metals from their ores (e.g., aluminium from bauxite).
- **Production of Chemicals:** Manufacturing chlorine, hydrogen, sodium hydroxide.
- **Anodizing:** Creating a protective oxide layer on metal surfaces (e.g., aluminium).

5.5 Faraday's Laws of Electrolysis

- **Faraday's First Law:** The mass of a substance deposited or liberated at an electrode is directly proportional to the quantity of electricity (charge) passed through the electrolyte. ($m \propto Q$ or $m = zQ = zIt$)
    - **z:** Electrochemical equivalent (mass per unit charge).
- **Faraday's Second Law:** When the same quantity of electricity is passed through different electrolytes, the masses of the substances deposited or liberated are directly proportional to their chemical equivalent masses (or equivalent weights).

- Chemical Equivalent Mass = $\frac{\text{Relative atomic mass}}{\text{Valency}}$

5.6 Conduction of Electricity Through Gases

- **Normal Gases:** Under normal conditions (atmospheric pressure, room temperature), gases are poor conductors of electricity (insulators) because their molecules are neutral and far apart.
- **Ionization:** Gases can become conductors if they are ionized. Ionization can occur due to:
    - **High Voltage:** Strong electric fields can strip electrons from gas atoms (e.g., lightning, neon signs).
    - **High Temperature:** Thermal energy causes collisions strong enough to ionize atoms.
    - **Radiation:** UV light, X-rays, or radioactive emissions can ionize gas molecules.
- **Discharge Tubes:** Devices where electricity is passed through gases at low pressure, producing glow discharge (e.g., fluorescent lamps, neon signs).

5.7 Hot Cathode: Thermionic Emission

- **Thermionic Emission:** The emission of electrons from a heated metal surface.
- **How it works:** When a metal is heated to a high enough temperature, the kinetic energy of its free electrons becomes sufficient to overcome the work function (binding energy) of the metal surface, allowing them to escape.
- **Applications:** Electron guns in cathode ray tubes (CRTs) like old TV screens, X-ray tubes, vacuum tubes.

5.8 Summary

- Electrolysis involves electric current driving chemical reactions in liquid electrolytes containing ions.
- Faraday's Laws quantify the amount of substance deposited during electrolysis.
- Gases are usually insulators but can conduct when ionized by high voltage, heat, or radiation.
- Thermionic emission is the release of electrons from heated metal, used in electron guns.

6. Magnetic Field

6.1 Concept of Magnetic Field

- **Definition:** A region of space around a magnet or a current-carrying conductor where a magnetic force can be detected.
- **Magnetic Field Lines:** Imaginary lines used to represent a magnetic field.
    - They emerge from the North pole and enter the South pole outside the magnet, forming continuous loops.
    - The density of lines indicates the strength of the field.
    - Lines never cross each other.
    - Tangent to the line at any point gives the direction of the magnetic field at that point (direction a compass would point).

6.2 Patterns of Magnetic Field

- **Around a Bar Magnet:** Lines emerge from N pole, loop around, and enter S pole. The field is strongest at the poles.
- **Around a Straight Current-Carrying Wire:** Concentric circles around the wire. Direction given by **Right-Hand Grip Rule** (thumb in current direction, fingers curl in field direction).
- **Around a Solenoid (Coil):** The field inside is strong and uniform, similar to a bar magnet, with field lines running parallel to the axis. Outside, it resembles a bar magnet's field. Direction also by Right-Hand Grip Rule (fingers in current direction, thumb points to North pole).

6.3 Methods of Making Magnets

- **Stroking Method:** Rubbing a magnetic material (like steel) with one pole of a strong permanent magnet in a single direction repeatedly.
- **Electrical Method (Electromagnetism):** Passing direct current (DC) through a coil of wire wrapped around a ferromagnetic material (like soft iron). The core becomes magnetized. This is the most effective and controllable method.
- **Induction:** Placing a magnetic material in a strong magnetic field for a long time.

6.4 Electromagnets and Their Application of Electromagnetic Field

- **Electromagnet:** A temporary magnet created by passing electric current through a coil of wire (solenoid) wrapped around a soft iron core. It's a temporary magnet because it loses its magnetism when the current is switched off.
- **Advantages:** Can be switched on/off, strength can be varied by changing current or number of turns.
- **Applications:**
    - **Cranes:** Lifting and moving heavy scrap metal.
    - **Electric Bells:** Striking a gong.
    - **Relays:** Electrically operated switches.
    - **Circuit Breakers:** Protecting electrical circuits.
    - **Loudspeakers, Microphones:** Converting electrical energy to sound and vice versa.

6.5 The Earth's Magnetic Field

- **Origin:** Believed to be generated by convection currents of molten iron in the Earth's outer core (dynamo effect).
- **Properties:** Behaves like a giant bar magnet tilted relative to the Earth's rotational axis. The Earth's magnetic North pole is actually a geographic South pole (where the magnetic field lines enter).
- **Importance:** Protects Earth from harmful charged particles from the solar wind (cosmic rays) by deflecting them. Responsible for auroras.

6.6 Magnetic Force on a Charge Moving in a Magnetic Field (Lorentz Force)

- **Principle:** A charged particle moving in a magnetic field experiences a force perpendicular to both its velocity and the magnetic field direction.
    - Formula: $F = qvB\sin\theta$ (where θ is angle between v and B).
    - **Direction:** Determined by **Fleming's Left-Hand Rule** (Thumb: Force, Forefinger: Field, Middle Finger: Current/Velocity of positive charge).

- **Applications:** Mass spectrometers, particle accelerators, Hall effect.

6.7 Summary

- Magnetic fields are regions of magnetic influence, represented by field lines.
- Magnetic fields are created by magnets or electric currents.
- Electromagnets offer controllable magnetism for various applications.
- Earth has a natural magnetic field protecting us.
- Moving charges experience a force in a magnetic field (Lorentz force).