Short Notes

SP015 Physics 1

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Contents

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1 Tips for Solving Physics Problems

1. **Understand the Problem:** Carefully read the problem. Identify what is given and what is required.
2. **Draw a Diagram:** Visualize the problem with a sketch or free-body diagram. Label all known and unknown quantities.
3. **List Known and Unknown Quantities:** Write down all given values and the quantity you are solving for.
4. **Choose the Right Equations:** Identify the physical principles involved (e.g., Newton's laws, conservation laws, kinematic equations).
5. **Check Units:** Ensure all quantities are in the correct SI units before performing calculations.
6. **Solve Symbolically First:** If possible, manipulate equations symbolically before substituting numbers.
7. **Substitute and Calculate:** Plug in known values and compute the result. Use appropriate significant figures.
8. **Check Your Answer:** Consider whether your answer makes sense physically. Check units and magnitude.
9. **Practice Regularly:** Consistent practice improves speed, confidence, and familiarity with problem types.
10. **Stay Calm and Organized:** Keep your work neat to avoid confusion and reduce mistakes.

2 Dimensional Analysis and Vectors

Dimensions of Physical Quantities

- **Dimension:** Represents the nature of a physical quantity with respect to basic physical quantities (e.g., mass $[M]$, length $[L]$, time $[T]$).
- Example: Velocity has dimension $[LT^{-1}]$

Derived Quantities

- Derived quantities are expressed in terms of base quantities.
- Example: Force $F = ma \Rightarrow [F] = [M][LT^{-2}] = [MLT^{-2}]$

Dimensional Homogeneity

Concept

Dimensional Homogeneity: An equation is dimensionally correct if all terms have the same dimensions.

Try It Yourself

Example: Check if $s = ut + \frac{1}{2}at^2$ is dimensionally correct.

$$[u] = [LT^{-1}], \quad [t] = [T], \quad [a] = [LT^{-2}] \Rightarrow [s] = [L]$$

All terms yield $[L]$; thus, the equation is dimensionally homogeneous.

Scalars and Vectors

- **Scalar:** Has only magnitude (e.g., mass, speed, energy).
- **Vector:** Has both magnitude and direction (e.g., velocity, force).

Vector Components

Concept

Resolving Vectors: Any vector $\vec{A}$ can be resolved into x and y components.

$$A_x = A\cos\theta, \quad A_y = A\sin\theta$$

Resultant of Vectors

- Resultant vector is the vector sum of all vectors.
- Use vector addition (head-to-tail or parallelogram method).
- For 2D vectors:

$$R = \sqrt{(\sum A_x)^2 + (\sum A_y)^2}, \quad \tan\theta = \frac{\sum A_y}{\sum A_x}$$

Try It Yourself

Example: Find the resultant of three vectors: $\vec{A} = 5\,\mathrm{N}$ east, $\vec{B} = 3\,\mathrm{N}$ north, and $\vec{C} = 4\,\mathrm{N}$ west.

- Resolve into components:
$$A_x = +5,\ B_y = +3,\ C_x = -4$$
- $\sum A_x = 5 - 4 = 1$, $\sum A_y = 3$
- $R = \sqrt{1^2 + 3^2} = \sqrt{10} \approx 3.16\,\mathrm{N}$
- $\theta = \tan^{-1}(3/1) = 71.6^\circ$ north of east

3 Kinematics

Describing Motion in One Dimension

Concept

Displacement vs Distance: Displacement is the change in position (can be negative), while distance is the total length traveled (always positive).

$$\Delta x = x_f - x_i$$

Concept

Velocity: Velocity is the rate of change of position. It has both magnitude and direction.

Average Velocity:

$$v_{\text{avg}} = \frac{\Delta x}{\Delta t}$$

Instantaneous Velocity:

$$v = \frac{\mathrm{d}x}{\mathrm{d}t}$$

Uniform Velocity: The object moves equal distances in equal time intervals. Acceleration is zero.

Concept

Acceleration: The rate at which velocity changes with time.

Average Acceleration:

$$a_{\text{avg}} = \frac{\Delta v}{\Delta t}$$

Instantaneous Acceleration:

$$a = \frac{\mathrm{d}v}{\mathrm{d}t}$$

Motion Graphs and Interpretation

- **Displacement-Time Graph:** Slope = velocity.
- **Velocity-Time Graph:** Slope = acceleration; Area = displacement.
- **Acceleration-Time Graph:** Area = change in velocity.

Equations of Motion for Constant Acceleration

Concept

Use these equations when acceleration is constant:

(1) $v = v_0 + at$

(2) $x = x_0 + v_0 t + \frac{1}{2}at^2$

(3) $v^2 = v_0^2 + 2a(x - x_0)$

(4) $x = x_0 + \frac{1}{2}(v_0 + v)t$

Projectile Motion

Concept

Projectile motion is 2D motion under the influence of gravity. Horizontal and vertical motions are independent.

Horizontal Launch

- Horizontal velocity is constant.
- Vertical motion is free fall.

$$\text{Horizontal: } x = v_0 t \quad \text{Vertical: } y = \frac{1}{2}gt^2$$

Launch at an Angle

$$v_{0x} = v_0 \cos\theta \quad \text{and} \quad v_{0y} = v_0 \sin\theta$$

$$\text{Horizontal: } x = v_{0x} t \quad \text{Vertical: } y = v_{0y} t - \frac{1}{2}gt^2$$

Key Formulas:

$$h_{\max} = \frac{v_{0y}^2}{2g}, \quad t = \frac{2v_{0y}}{g}, \quad R = \frac{v_0^2 \sin(2\theta)}{g}$$

Try It Yourself

Example: A ball is launched at 25 m/s at 40°. Find its range.

$$v_{0x} = 25\cos(40^\circ), \quad v_{0y} = 25\sin(40^\circ)$$

$$t = \frac{2v_{0y}}{g}, \quad R = v_{0x} t$$

Watch Out!

Don't mix horizontal and vertical equations. Treat them separately!

4 Momentum and Newton's Laws of Motion

Concept

Momentum: Momentum is the product of an object's mass and its velocity. It is a vector quantity.

$$\vec{p} = m\vec{v}$$

Concept

Impulse: Impulse is the product of force and the time interval over which it acts. It equals the change in momentum.

$$\vec{J} = \vec{F}\Delta t = \Delta\vec{p}$$

Impulse-Momentum Theorem

$$\vec{F}\Delta t = m\vec{v}_f - m\vec{v}_i$$

Try It Yourself

Example: A 2 kg ball initially moving at 3 m/s comes to rest in 0.5 s. What is the impulse?

$$J = \Delta p = m(v_f - v_i) = 2(0 - 3) = -6\,\mathrm{N \cdot s}$$

Impulse from Force-Time Graphs

- The area under a force-time graph equals the impulse.

Conservation of Momentum

Concept

Principle: If no external forces act on a system, the total momentum of the system remains constant.

$$\vec{p}_{\text{total, before}} = \vec{p}_{\text{total, after}}$$

Collisions

- **Elastic Collision:** Both momentum and kinetic energy are conserved.
- **Inelastic Collision:** Momentum is conserved, but kinetic energy is not.
- **Perfectly Inelastic:** Objects stick together after the collision.

2D Collisions

Apply conservation of momentum independently in the x and y directions:

$$m_1 v_{1x} + m_2 v_{2x} = m_1 v'_{1x} + m_2 v'_{2x}$$

$$m_1 v_{1y} + m_2 v_{2y} = m_1 v'_{1y} + m_2 v'_{2y}$$

Try It Yourself

Try This: Two carts collide on a frictionless surface. Use momentum conservation to find final velocities.

Forces and Newton's Laws

Common Forces

- **Weight (W):** $W = mg$
- **Normal Force (N):** Perpendicular support force from a surface.
- **Tension (T):** Force transmitted by a string or rope.
- **Friction (f):** Opposes motion; depends on normal force.
- **External Force (F):** Any additional applied force.

Free Body Diagrams (FBD)

- Draw all forces acting on an object.
- Represent forces as arrows pointing in the direction of action.

Static and Kinetic Friction

$$f_s \leq \mu_s N \quad \text{(Static)}$$
$$f_k = \mu_k N \quad \text{(Kinetic)}$$

Watch Out!

Static friction adjusts up to its maximum value to prevent motion. **Kinetic friction** is constant once the object is moving.

Newton's Laws of Motion

1. **First Law (Inertia):** An object remains at rest or in uniform motion unless acted upon by a net external force.
2. **Second Law:** $\sum \vec{F} = m\vec{a}$
3. **Third Law:** For every action, there is an equal and opposite reaction.

Applying Newton's Laws

- Identify all forces.
- Draw the FBD.
- Apply $\sum \vec{F} = m\vec{a}$ in each direction.

Try It Yourself

Example: A box on a rough surface is pulled with a rope at an angle. Find the acceleration.

5 Work, Energy, and Power

Concept

Work and the Scalar Product: Work is the scalar product (dot product) of force and displacement vectors. It measures the energy transferred by a force acting over a distance.

$$W = \vec{F} \cdot \vec{d} = Fd\cos\theta$$

Physical Meaning: Only the component of force in the direction of displacement does work. If $\theta = 90^\circ$, $\cos\theta = 0$ and no work is done.

Work by a Constant Force

- Force must be constant in magnitude and direction.
- Displacement must be in a straight line.

Try It Yourself

Example: A 10 N force acts at an angle of 30° to the direction of motion over 5 m. Find the work done.

$$W = Fd\cos\theta = 10 \times 5 \times \cos(30^\circ) = 43.3\,\text{J}$$

Force-Displacement Graphs

- The area under the graph equals the work done.
- For variable force, break into segments or integrate if needed.

Forms of Mechanical Energy

Concept

Kinetic Energy: Energy due to motion.

$$KE = \frac{1}{2}mv^2$$

Concept

Gravitational Potential Energy: Energy due to position in a gravitational field.

$$PE_g = mgh$$

Concept

Elastic Potential Energy: Stored energy in a stretched or compressed spring.

$$PE_s = \frac{1}{2}kx^2$$

Conservation of Mechanical Energy

Concept

In the absence of non-conservative forces (like friction), the total mechanical energy remains constant:

$$E_{\text{mechanical}} = KE + PE = \text{constant}$$

Try It Yourself

Example: A ball is dropped from a height of 10 m. Find its speed just before hitting the ground.

$$mgh = \frac{1}{2}mv^2 \Rightarrow v = \sqrt{2gh}$$
$$v = \sqrt{2 \times 9.8 \times 10} = 14.0\,\text{m/s}$$

Work-Energy Theorem

Concept

Work done by the net force on an object equals its change in kinetic energy.

$$W_{\text{net}} = \Delta KE = \frac{1}{2}mv^2 - \frac{1}{2}mv_0^2$$

Power

Concept

Average Power: Rate at which work is done over time.

$$P_{\text{avg}} = \frac{W}{t}$$

Concept

Instantaneous Power: The dot product of force and velocity at a given instant.

$$P = \vec{F} \cdot \vec{v} = Fv\cos\theta$$

Try It Yourself

Example: A car engine does 10 000 J of work in 5 s. What is its average power?

$$P = \frac{10000}{5} = 2000\,\text{W}$$

6 Uniform Circular Motion and Centripetal Force

Angular Quantities

Concept

Angular Displacement (θ): The angle through which an object moves on a circular path, measured in radians.

- $\theta = \frac{s}{r}$ where s is arc length and r is radius.

Concept

Period (T): Time taken for one complete revolution.

Concept

Frequency (f): Number of revolutions per second.

$$f = \frac{1}{T}$$

Concept

Angular Velocity (ω): Rate of change of angular displacement.

$$\omega = \frac{\theta}{t} = 2\pi f = \frac{2\pi}{T}$$

Unit Conversions

- $360° = 2\pi$ radians
- 1 revolution $= 2\pi$ radians
- Use: degrees $\times \frac{\pi}{180} =$ radians

Uniform Circular Motion

- Object moves in a circle at constant speed.
- Direction of velocity changes, so object is accelerating.

Concept

Centripetal Acceleration (a_c): Acceleration directed toward the center of the circle.

$$a_c = \frac{v^2}{r} = \omega^2 r$$

Concept

Centripetal Force (F_c): Net force causing centripetal acceleration.

$$F_c = ma_c = m\frac{v^2}{r} = m\omega^2 r$$

Try It Yourself

Example: A 1.0 kg object moves in a circle of radius 2.0 m at 3.0 m/s. Find the centripetal force.

$$F_c = \frac{(1)(3)^2}{2} = 4.5\,\mathrm{N}$$

Special Cases of Uniform Circular Motion

1. Horizontal Circle (e.g., mass on a string on a frictionless table)

- Tension provides centripetal force.
- $T = \frac{mv^2}{r}$

2. Vertical Circle (e.g., a pendulum or roller coaster loop)

- Tension and weight both affect net force.
- At top: $T + mg = \frac{mv^2}{r}$
- At bottom: $T - mg = \frac{mv^2}{r}$

3. Conical Pendulum (e.g., mass on a string moving in horizontal circle)

- Tension has vertical (balances mg) and horizontal (provides F_c) components.
- Use trigonometry: $T\cos\theta = mg$, $T\sin\theta = \frac{mv^2}{r}$

Try It Yourself

Example: A 0.5 kg mass moves in a horizontal circle of radius 1.0 m at 2.0 m/s. Find the tension in the string if the angle is 30°.

$$F_c = \frac{mv^2}{r} = \frac{0.5 \times 4}{1} = 2.0\,\mathrm{N}$$

$$T = \frac{F_c}{\sin\theta} = \frac{2.0}{\sin(30^\circ)} = 4.0\,\mathrm{N}$$

7 Simple Harmonic Motion (SHM)

What is SHM?

Concept

Simple Harmonic Motion (SHM): A type of periodic motion where the restoring force is directly proportional to displacement and directed toward the equilibrium position.

$$F = -kx$$

- SHM is characterized by sinusoidal functions.
- Occurs in systems like springs and pendulums.

Displacement in SHM

$$x(t) = A\sin(\omega t + \phi)$$

- A: Amplitude
- ω: Angular frequency $\left(\omega = \sqrt{\frac{k}{m}}\right)$
- ϕ: Phase constant

Velocity in SHM

- As a function of time:
$$v(t) = \frac{dx}{dt} = A\omega\cos(\omega t + \phi)$$
- As a function of displacement:
$$v(x) = \omega\sqrt{A^2 - x^2}$$

Acceleration in SHM

- As a function of time:
$$a(t) = -A\omega^2\sin(\omega t + \phi)$$
- As a function of displacement:
$$a(x) = -\omega^2 x$$

Energy in SHM

- Kinetic Energy:
$$KE = \frac{1}{2}mv^2 = \frac{1}{2}m\omega^2(A^2 - x^2)$$
- Potential Energy:
$$PE = \frac{1}{2}kx^2 = \frac{1}{2}m\omega^2x^2$$
- Total Mechanical Energy:
$$E = KE + PE = \frac{1}{2}kA^2 = \text{constant}$$
- Total energy depends on the square of the amplitude.

Graphs in SHM

- Displacement-time: sine or cosine wave
- Velocity-time: cosine or sine wave (shifted)
- Acceleration-time: inverted sine wave
- Energy-displacement:
  - KE is maximum at $x = 0$, zero at $x = \pm A$
  - PE is zero at $x = 0$, maximum at $x = \pm A$
  - Total energy remains constant

Period of SHM

- Mass-spring system:

$$T = 2\pi\sqrt{\frac{m}{k}}$$

- Simple pendulum:

$$T = 2\pi\sqrt{\frac{L}{g}}$$

Try It Yourself

Example: A 0.2 kg mass is attached to a spring with $k = 50\,\mathrm{N/m}$. Find the period of oscillation.

$$T = 2\pi\sqrt{\frac{0.2}{50}} = 2\pi\sqrt{0.004} \approx 0.4\,\mathrm{s}$$

8 Waves and Sound

Wave Characteristics

Concept

Wavelength (λ): The distance between two consecutive points that are in phase (e.g., crest to crest or trough to trough).

Concept

Wavenumber (k): The number of wave cycles per unit distance.

$$k = \frac{2\pi}{\lambda}$$

Progressive Waves

A progressive (traveling) wave moves energy through a medium without transporting matter.

Concept

Wave Equation:

$$y(x,t) = A\sin(kx - \omega t + \phi)$$

Wave vs Particle Velocity

- **Particle Vibrational Velocity:** Speed of oscillation of particles in the medium.

$$v_p(t) = \frac{\partial y}{\partial t} = A\omega\cos(kx - \omega t + \phi)$$

- **Wave Propagation Velocity:** Speed at which the wave form travels.

$$v = f\lambda = \frac{\omega}{k}$$

Displacement-Time and Displacement-Distance Graphs

- **Displacement-Time:** Fixed location, plots y vs t (shows oscillation).
- **Displacement-Distance:** Fixed time, plots y vs x (shows wave shape).

Wave Interference and Superposition

Concept

Principle of Superposition: When two or more waves overlap, the resultant displacement is the vector sum of the individual displacements.

- **Constructive Interference:** Waves in phase increase amplitude.
- **Destructive Interference:** Waves out of phase cancel each other.

Standing Waves

Concept

Standing Wave Equation:

$$y(x,t) = 2A\sin(kx)\cos(\omega t)$$

- Formed by the superposition of two identical waves traveling in opposite directions.
- Nodes: points of no motion.
- Antinodes: points of maximum motion.

Progressive vs Standing Waves

- **Progressive:** Energy travels, all particles oscillate with same amplitude.
- **Standing:** Energy trapped, particles oscillate with varying amplitude.

Resonance in Strings and Air Columns

1. Stretched String (both ends fixed)

$$f_n = \frac{n}{2L}v, \quad n = 1, 2, 3, \ldots$$

2. Open-Ended Air Column (both ends open)

$$f_n = \frac{n}{2L}v, \quad n = 1, 2, 3, \ldots$$

3. Closed-Ended Air Column (one end closed)

$$f_n = \frac{n}{4L}v, \quad n = 1, 3, 5, \ldots$$

Doppler Effect

Concept

Doppler Effect: Apparent change in frequency due to relative motion between source and observer.

1. Moving Source, Stationary Observer

$$f' = \frac{f}{1 \pm \frac{v_s}{v}}$$

- Use $-$ when source moves toward observer
- Use $+$ when source moves away

2. Moving Observer, Stationary Source

$$f' = f\left(1 \pm \frac{v_o}{v}\right)$$

- Use + when observer moves toward source
- Use − when observer moves away

Try It Yourself

Example: A 500 Hz sound source moves toward a stationary observer at 30 m/s. Speed of sound is 340 m/s. Find the observed frequency.

$$f' = \frac{500}{1 - \frac{30}{340}} = \frac{500}{0.9118} \approx 548.2\,\text{Hz}$$

9 Young's Modulus, Heat Transfer and Heat Expansion

Stress and Strain

Concept

Stress (σ): Force applied per unit cross-sectional area.

$$\sigma = \frac{F}{A}$$

Concept

Strain (ε): Relative change in length.

$$\varepsilon = \frac{\Delta L}{L_0}$$

- **Tensile stress/strain:** Pulling force.
- **Compressive stress/strain:** Pushing force.

Stress-Strain Graph

- **Proportional limit:** Hooke's law obeyed.
- **Elastic region:** Material returns to original shape.
- **Yield point:** Permanent deformation begins.
- **Plastic region:** Irreversible deformation.
- **Ultimate tensile strength:** Maximum stress before breaking.

Elastic and Plastic Deformation

- **Elastic:** Material returns to original shape (reversible).
- **Plastic:** Permanent deformation occurs (irreversible).

Force-Elongation Graphs

- **Brittle material:** Sharp break with little elongation.
- **Ductile material:** Significant elongation before fracture.

Young's Modulus

Concept

Young's Modulus (E): Ratio of stress to strain within elastic limit.

$$E = \frac{\sigma}{\varepsilon} = \frac{FL_0}{A\Delta L}$$

Strain Energy

- **From Force-Elongation Graph:**

$$U = \frac{1}{2}F\Delta L$$

- **Strain Energy per Unit Volume:**

$$u = \frac{1}{2}\sigma\varepsilon$$

Heat Conduction

Concept

Heat conduction: Transfer of heat through a material without movement of the material.

Concept

Rate of heat transfer:

$$Q = \frac{kA(\Delta T)}{L}$$

Where k is thermal conductivity, A is cross-sectional area, ΔT is temperature difference, and L is thickness.

- For two rods in series:

$$Q = \frac{\Delta T}{\left(\frac{L_1}{k_1 A} + \frac{L_2}{k_2 A}\right)}$$

Temperature-Distance Graph Analysis

- **Insulated rod:** Linear temperature gradient.
- **Non-insulated:** May show heat loss; gradient not linear.

Thermal Expansion

- **Linear expansion:**

$$\Delta L = \alpha L_0 \Delta T$$

- **Area expansion:**

$$\Delta A = 2\alpha A_0 \Delta T$$

- **Volume expansion:**

$$\Delta V = 3\alpha V_0 \Delta T$$

- **Expansion of liquid in container:** Effective expansion is liquid minus container expansion.

Try It Yourself

Example: An aluminum rod ($\alpha = 23 \times 10^{-6}/°C$) of length 1.0 m is heated from 20 °C to 100 °C. Find the change in length.

$$\Delta L = 23 \times 10^{-6} \times 1.0 \times (100 - 20) = 1.84 \times 10^{-3}\,\text{m} = 1.84\,\text{mm}$$

10 Kinetic Theory and Thermodynamics

Kinetic Theory of Gases

- Gas consists of large number of small particles in random motion.
- Collisions between particles and container walls are elastic.
- Volume of gas particles is negligible compared to container volume.
- No intermolecular forces except during collisions.
- Time of collision is negligible.

Root Mean Square (RMS) Speed

Concept

RMS speed: The square root of the average of the squares of molecular speeds.

$$v_{\text{rms}} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{M}}$$

Where k is Boltzmann constant, R is gas constant, T is temperature, m is mass of one molecule, and M is molar mass.

Ideal Gas Equation and RMS Speed

- Using ideal gas law $PV = nRT$:

  $$v_{\text{rms}} = \sqrt{\frac{3P}{\rho}}$$

  Where ρ is the density of the gas.

Translational Kinetic Energy

Concept

Average translational kinetic energy per molecule:

$$K_{\text{avg}} = \frac{3}{2}kT$$

Degrees of Freedom

- **Degree of freedom:** Independent mode of motion.
- Monoatomic: 3 translational (3 DoF)
- Diatomic: 3 translational + 2 rotational = 5 DoF (at room temperature)
- Polyatomic: 3 translational + 3 rotational = 6 DoF

Equipartition of Energy

- Each degree of freedom contributes $\frac{1}{2}kT$ to average energy per molecule.

Internal Energy of an Ideal Gas

Concept

Total internal energy for n moles:

$$U = \frac{f}{2} nRT$$

Where f is the number of degrees of freedom.

First Law of Thermodynamics

Concept

Statement:

$$\Delta U = Q - W$$

Where ΔU is change in internal energy, Q is heat added to system, and W is work done by system.

Thermodynamic Processes

- **Isothermal:** $T = \text{const}$, $\Delta U = 0$
- **Isochoric:** $V = \text{const}$, $W = 0$
- **Isobaric:** $P = \text{const}$
- **Adiabatic:** $Q = 0$

Pressure-Volume Graphs

- Area under P-V curve = Work done by gas

Work Done in Processes

- **Isothermal:**
$$W = nRT \ln\left(\frac{V_f}{V_i}\right)$$
- **Isochoric:**
$$W = 0$$
- **Isobaric:**
$$W = P(V_f - V_i)$$

Try It Yourself

Example: One mole of ideal gas expands isothermally from 1.0 L to 2.0 L at 300 K. Find the work done.

$$W = (8.314)(300) \ln\left(\frac{2.0}{1.0}\right) = 1729.3\,\text{J}$$