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DEPARTMENT OF PHYSICS

STUDY NOTES

SPHYCT1101

Fundamentals of Physics – I

B.Sc. First Year (Semester I)

NEP 2020 Pattern | Major 1 | 2 Credits

Unit I: Gravitation • Unit II: Fluids
Unit III: Sound • Unit IV: Semiconductor Physics

For internal use of students. Prepared as a study aid; students should also refer to prescribed textbooks.

By
Dr Narsingh

Course Information & Exam Pattern

Teaching and Assessment Scheme

Course Code	Course Name	Theory Hrs	Credits	CA (T1 + T2 avg)	ESA	Total
SPHYCT1101	Fundamentals of Physics-I	02 hrs/week	02	10 + 10 → avg 10	40 *	50

* As given in the scheme, the Continual Assessment (CA) component consists of Test I and Test II (average taken) and the Semester End Assessment (ESA) is the written theory paper. The theory question paper is of 30 marks and 2 hours duration (see below).

Syllabus at a Glance (30 Hours)

Unit	Title	Topics	Hrs
I	Gravitation	Newton's law of gravitation; central force motion; gravitational field and potential; potential of spherical shell; Kepler's laws	07
II	Fluids	Density & pressure; Pascal's principle; Archimedes' principle; Bernoulli's equation; viscosity; streamline flow	08
III	Sound	Origin and types of sound; velocity in air and water; Newton's formula; Laplace correction; intensity; effect of T, P, humidity	08
IV	Semiconductor Physics	Intrinsic & extrinsic semiconductors; P-N junction; Zener diode and regulator; LED; photodiode	07
	Total		30

Semester End Assessment – Question Paper Pattern

B.Sc. First/Second Year Physics | Time: 2 Hours | Total Marks: 30 | NEP-2020 Pattern

- All questions carry equal marks (10 marks each).
- Question 1 is compulsory:** four short questions of 2.5 marks each, one from each Unit (I to IV).
- Attempt any TWO** of the remaining four questions (Q.2 to Q.5). Each of these is based on one Unit and has two sub-questions of 5 marks each.
- Figures to the right indicate full marks.

Question	Based on	Format	Marks
Q.1 (compulsory)	Units I, II, III, IV	a), b), c), d) – 2.5 marks each	10
Q.2	Unit I – Gravitation	a) 5 marks, b) 5 marks	10
Q.3	Unit II – Fluids	a) 5 marks, b) 5 marks	10
Q.4	Unit III – Sound	a) 5 marks, b) 5 marks	10
Q.5	Unit IV – Semiconductor Physics	a) 5 marks, b) 5 marks	10

How to use these notes

- Read each unit in order; every topic number (1.1, 1.2 ...) matches the university syllabus.
- Learn the definitions, statements and derivations marked in the boxes — these are the usual 5-mark questions.

3. Solve the numerical examples yourself before looking at the solution.
4. Use the Question Bank and Formula Sheet at the end for revision before tests and the semester exam.

Useful constants

$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$ | $g = 9.8 \text{ m/s}^2$ | Mass of Earth $M_e = 5.98 \times 10^{24} \text{ kg}$ | Radius of Earth $R_e = 6.4 \times 10^6 \text{ m}$

1 atm = $1.013 \times 10^5 \text{ Pa}$ | Density of water = 1000 kg/m^3 | Density of mercury = 13600 kg/m^3
Speed of sound in air at $0^\circ \text{C} \approx 332 \text{ m/s}$ | Charge of electron $e = 1.6 \times 10^{-19} \text{ C}$ | $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

UNIT I: GRAVITATION

Gravitation is the universal force of attraction acting between all bodies in the universe, from falling apples to orbiting planets. It is the weakest of the four fundamental forces, yet it governs the motion of planets, stars and galaxies because it is always attractive and acts over very large distances.

1.1 Newton's Law of Gravitation

Statement

Every particle in the universe attracts every other particle with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. The force acts along the line joining the two particles.

$$F = G m_1 m_2 / r^2$$

Here m_1 and m_2 are the masses, r is the distance between their centres and G is the **universal gravitational constant**. In vector form, the force on m_2 due to m_1 is

$$F_{21} = - (G m_1 m_2 / r^2) \hat{r}_{12} \text{ (negative sign: the force is attractive)}$$

Universal gravitational constant (G)

- If $m_1 = m_2 = 1$ kg and $r = 1$ m then $F = G$. Thus G is numerically equal to the force of attraction between two 1 kg masses placed 1 m apart.
- Value: $G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$. Unit: $\text{N m}^2 \text{ kg}^{-2}$. Dimensions: $[\text{M}^{-1} \text{L}^3 \text{T}^{-2}]$.
- G is a universal constant: it does not depend on the medium, the masses or the temperature. It was first measured by Henry Cavendish (1798) using a torsion balance.

Derivation of the law (from Kepler's third law)

Consider a planet of mass m moving in a circular orbit of radius r around the Sun with speed v and period T . The necessary centripetal force is supplied by the Sun's attraction.

$$F = m v^2 / r, \quad v = 2\pi r / T \Rightarrow F = 4\pi^2 m r / T^2$$

Kepler's third law states $T^2 = k r^3$ (k is constant for all planets). Substituting,

$$F = 4\pi^2 m r / (k r^3) = (4\pi^2 / k) \cdot m / r^2$$

So $F \propto m / r^2$. By Newton's third law, the force exerted by the Sun on the planet equals that exerted by the planet on the Sun. The Sun's force must therefore also be proportional to the Sun's mass M , i.e. $F \propto M m$. Combining both results:

$$F \propto M m / r^2 \Rightarrow F = G M m / r^2$$

where G is the constant of proportionality. This is Newton's law of gravitation.

Important properties of the gravitational force

- It is always attractive and acts along the line joining the centres of the two bodies.
- It forms an action–reaction pair (equal and opposite forces, Newton's third law).
- It is a central and conservative force: work done depends only on the initial and final positions.
- It is independent of the medium between the masses and is the weakest of the fundamental forces.
- For spherical bodies, the mass can be considered concentrated at the centre.

Acceleration due to gravity (g) and mass of the Earth

For a body of mass m on the surface of the Earth (mass M_e , radius R_e), the weight mg equals the gravitational force:

$$m g = G M_e m / R_e^2 \Rightarrow g = G M_e / R_e^2$$

Hence g does not depend on the mass of the falling body. Using $g = 9.8 \text{ m/s}^2$, $R_e = 6.4 \times 10^6 \text{ m}$ we get $M_e = g R_e^2 / G \approx 6.0 \times 10^{24} \text{ kg}$. At height h above the surface $g' = g (1 + h/R_e)^{-2} \approx g (1 - 2h/R_e)$, and at depth d inside the Earth $g' = g (1 - d/R_e)$. The value of g is least at the equator and greatest at the poles.

Solved Numerical 1

Q. Calculate the gravitational force between two bodies of masses 50 kg and 80 kg kept 2 m apart.

Sol. $F = G m_1 m_2 / r^2 = (6.67 \times 10^{-11} \times 50 \times 80) / (2)^2 = (6.67 \times 10^{-11} \times 4000) / 4 = \mathbf{6.67 \times 10^{-8} \text{ N}}$.

1.2 Motion of a Particle in a Central Force Field

A **central force** is a force which at every point acts along the line joining the particle to a fixed point O (the centre of force) and whose magnitude depends only on the distance r from O . We write $F = f(r) \hat{r}$. Gravitation (and the electrostatic force) are examples.

Three important results follow for a particle moving under a central force. Let r be the position vector from O and $p = mv$ the linear momentum.

(a) Angular momentum is conserved

Torque about O is $\tau = r \times F = r \times f(r) \hat{r} = 0$ because r is parallel to $\hat{r}$. Since $\tau = dL/dt$,

$$dL/dt = 0 \Rightarrow L = r \times m v = \text{constant (in magnitude and direction)}$$

(b) The motion takes place in a plane

$L = r \times mv$ is perpendicular to both r and v . Since L is constant in direction, r and v always lie in the plane perpendicular to L . Hence the particle moves in a single fixed plane that contains the centre of force.

(c) Areal velocity is constant

In a small time dt the particle moves from P to Q , with displacement $dr = v dt$. The radius vector sweeps a thin triangle of area

$$dA = \frac{1}{2} |r \times dr| = \frac{1}{2} |r \times v| dt$$

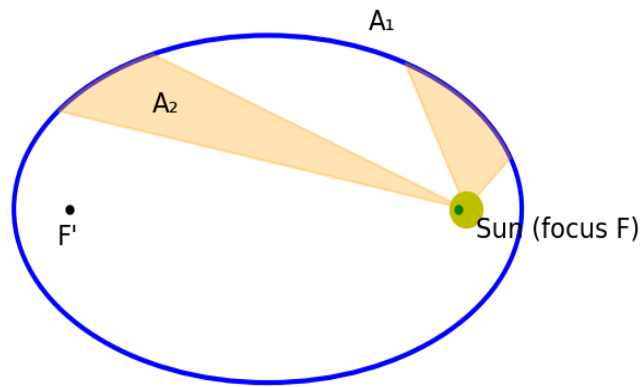
So the areal velocity (rate of sweeping area) is

$$dA/dt = \frac{1}{2} |r \times v| = L / (2m) = \text{constant}$$

In polar coordinates (r, θ), $L = m r^2 (d\theta/dt)$, so $dA/dt = \frac{1}{2} r^2 (d\theta/dt) = \text{constant}$. This is the mathematical form of Kepler's second law — the radius vector from the Sun to a planet sweeps out equal areas in equal intervals of time.

Key points to remember

- Central force $\Rightarrow$ zero torque $\Rightarrow L = \text{constant}$.
- $L = \text{constant} \Rightarrow$ motion is planar.
- $dA/dt = L/2m = \text{constant} \Rightarrow$ equal areas in equal times (a consequence of conservation of angular momentum, NOT of the inverse-square nature).
- When a planet is closer to the Sun (r small) it moves faster, since $L = m r v$ remains constant at perihelion and aphelion.



Equal areas in equal times: $A_1 = A_2$

Fig. 1.1: Equal areas swept in equal times ($A_1 = A_2$)

1.3 Gravitational Field and Gravitational Potential

Gravitational field (intensity)

The region around a mass in which another mass experiences a gravitational force is called its gravitational field. The **gravitational field intensity** at a point is the force per unit mass experienced by a small test mass placed there:

$$I = F / m_0$$

For a point mass M , at distance r :

$$I = -GM/r^2 \hat{r} \text{ (directed towards } M; \text{ unit } N/kg = m/s^2)$$

On the Earth's surface the field intensity equals the acceleration due to gravity g .

Gravitational potential

Definition

Gravitational potential at a point is the work done in bringing a unit mass from infinity to that point (without acceleration). Unit: J/kg. Dimensions: $[L^2 T^{-2}]$.

Work done by the field when a unit mass is moved from ∞ to a point at distance r is the negative of the work done against the field:

$$V = - \int_r^\infty I dr \rightarrow V = \int_\infty^r (-GM/x^2) dx = -GM/r$$

The potential is negative everywhere (attractive force) and tends to zero at infinity, where it is maximum.

Relation between field and potential

$$I = -dV/dr$$

The field equals the negative gradient of the potential. Check: $V = -GM/r \Rightarrow -dV/dr = -GM/r^2$, which agrees with the expression for I .

Gravitational potential energy, escape and orbital velocity

- Potential energy of a mass m at distance r : $U = mV = -GMm/r$.
- **Escape velocity**: minimum speed to escape the Earth's field: $\frac{1}{2}mv_e^2 - GMm/R = 0 \Rightarrow v_e = \sqrt{2GM/R} = \sqrt{2gR} \approx \mathbf{11.2 \text{ km/s}}$.
- **Orbital velocity** (just above the surface): $mv_o^2/R = GMm/R^2 \Rightarrow v_o = \sqrt{gR} \approx \mathbf{7.9 \text{ km/s}}$; note $v_e = \sqrt{2} \cdot v_o$.

Solved Numerical 2

Q. Find the gravitational potential at the surface of the Earth. ($M_e = 6 \times 10^{24} \text{ kg}$, $R_e = 6.4 \times 10^6 \text{ m}$)

Sol. $V = -GM_e/R_e = -(6.67 \times 10^{-11} \times 6 \times 10^{24}) / (6.4 \times 10^6) \approx \mathbf{-6.25 \times 10^7 \text{ J/kg}}$.

1.4 Gravitational Potential due to a Spherical Shell

Problem: A thin uniform spherical shell has mass M and radius a . Find the gravitational potential at a point P at distance r from its centre O , when P is (i) outside ($r > a$) and (ii) inside ($r < a$) the shell.

Derivation

Divide the shell into thin circular rings by planes perpendicular to OP . Take a ring subtending angle θ at O with width $a d\theta$. Its radius is $a \sin \theta$, so its area is $(2\pi a \sin \theta)(a d\theta) = 2\pi a^2 \sin \theta d\theta$. The mass per unit area is $M / 4\pi a^2$, giving the ring mass

$$dm = (M / 4\pi a^2)(2\pi a^2 \sin \theta d\theta) = (M/2) \sin \theta d\theta$$

All points of the ring are at the same distance x from P . From triangle OPA (cosine rule): $x^2 = a^2 + r^2 - 2ar \cos \theta$. Differentiating: $2x dx = 2ar \sin \theta d\theta$, i.e. $\sin \theta d\theta = x dx / (ar)$. Potential at P due to the ring:

$$dV = -G dm / x = - (G M / 2) (\sin \theta d\theta) / x = - (G M / 2 a r) dx$$

Potential due to the whole shell is obtained by integrating over x from $x_{\min}$ to $x_{\max}$:

$$V = - (G M / 2 a r) [x] = - (G M / 2 a r) (x_{\max} - x_{\min})$$

Case (i): Point outside the shell ($r > a$)

x varies from $(r - a)$ to $(r + a)$: $x_{\max} - x_{\min} = 2a$

$V = -G M / r$ — the shell behaves as if all its mass were concentrated at its centre.

Case (ii): Point inside the shell ($r < a$)

x varies from $(a - r)$ to $(a + r)$: $x_{\max} - x_{\min} = 2r$

$V = -G M / a$ — constant, independent of r . Therefore field $I = -dV/dr = 0$ inside a hollow shell.

Case (iii): On the surface ($r = a$)

$V = -G M / a$ (both results agree at $r = a$, so the potential is continuous).

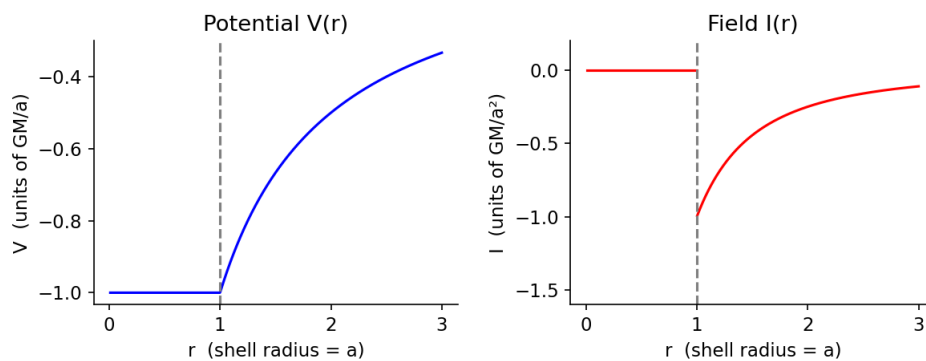


Fig. 1.2: Potential and field of a uniform spherical shell

Conclusion: Outside the shell the potential varies as $1/r$ and the field as $1/r^2$. Inside, the potential is constant and equal to its surface value, while the gravitational field is zero.

1.5 Kepler's Laws of Planetary Motion (Statement Only)

Law	Statement
First law (Law of orbits)	Every planet moves around the Sun in an elliptical orbit, with the Sun situated at one of the foci of the ellipse.
Second law (Law of areas)	The line joining the Sun and a planet sweeps out equal areas in equal intervals of time. (Areal velocity is constant.)
Third law (Law of periods)	The square of the period of revolution of a planet is directly proportional to the cube of the semi-major axis of its orbit: $T^2 \propto a^3$.

- Second law $\Leftarrow$ conservation of angular momentum; Third law $\Leftarrow$ inverse-square law of gravitation (for circular orbits $T^2 = 4\pi^2 r^3 / G M$).
- Planet is fastest at perihelion (closest point) and slowest at aphelion (farthest point).

Solved Numerical 3

Q. A planet has orbital radius 4 times that of the Earth. Find its time period (in years).

Sol. $T^2 \propto r^3 \Rightarrow (T/1 \text{ yr})^2 = (4)^3 = 64 \Rightarrow T = 8 \text{ years}.$

Quick revision – Unit I

- **Gravitational force** is central, conservative, always attractive and obeys the inverse-square law.
- $g = GM/R^2$ depends on the planet's mass and radius, not on the mass of the falling body.
- **Potential** $V = -GM/r$ (zero at infinity, negative elsewhere); **field** $I = -dV/dr = -GM/r^2$.
- Spherical shell: $V = -GM/r$ (outside), $V = -GM/a$ (inside, constant), field = 0 inside.
- Kepler II is a direct result of conservation of angular momentum; Kepler III follows from the inverse-square law.

Solved Numerical 4A

Q. Find the acceleration due to gravity at a height of 6400 km above the Earth's surface ($g = 9.8 \text{ m/s}^2$, $R_e = 6400 \text{ km}$).

Sol. $g' = g R_e^2 / (R_e + h)^2 = 9.8 \times (6400)^2 / (12800)^2 = 9.8 / 4 = 2.45 \text{ m/s}^2.$

Solved Numerical 4B

Q. Calculate the escape velocity from the Earth ($g = 9.8 \text{ m/s}^2$, $R_e = 6.4 \times 10^6 \text{ m}$).

Sol. $v_e = \sqrt{2 g R} = \sqrt{2 \times 9.8 \times 6.4 \times 10^6} = \sqrt{1.2544 \times 10^8} \approx 1.12 \times 10^4 \text{ m/s} = 11.2 \text{ km/s}.$

Frequently asked 2.5-mark questions (with answers)

Question	Answer
Why is G called a universal constant?	Its value is the same everywhere in the universe and for all pairs of masses, and it does not depend on the medium.
Why does the Moon not fall onto the Earth?	The Earth's gravitational pull provides the centripetal force for the Moon's orbital motion; the Moon is continuously "falling" around the Earth.
Why is areal velocity constant for a central force?	Torque is zero, so angular momentum $L = m r^2 d\theta/dt$ is constant, and $dA/dt = L/2m$.
What is the value of potential at infinity?	Zero (the reference point).

Short answer questions – Unit I

1. State Newton's law of gravitation. Write the dimensions of G.
2. What is a central force? Give two examples.
3. Define gravitational potential and gravitational field. How are they related?
4. What is the value of gravitational field inside a hollow spherical shell? Why?
5. State Kepler's three laws.

UNIT II: FLUIDS

A **fluid** is a substance that can flow and takes the shape of its container. Liquids and gases are fluids. Unlike solids, fluids cannot sustain a shear stress at rest. Fluid mechanics is divided into fluid statics (fluids at rest) and fluid dynamics (fluids in motion).

2.1 Fluids, Density and Pressure; Measuring Pressure

Density

The density of a substance is its mass per unit volume:

$$\rho = m / V \text{ (SI unit: kg/m}^3\text{; dimensions [M L}^{-3}\text{])}$$

Relative density (specific gravity) = density of substance / density of water at 4 °C (a pure number).

Density of liquids changes little with pressure (nearly incompressible), while that of gases changes considerably.

Pressure

Pressure is the normal force exerted per unit area on a surface: $P = F / A$. SI unit is the pascal (1 Pa = 1 N/m²). Other units: 1 atm = 1.013 × 10⁵ Pa = 76 cm of Hg = 760 torr; 1 bar = 10⁵ Pa. Pressure is a scalar; at a point in a fluid at rest it acts equally in all directions.

Variation of pressure with depth

Consider a horizontal layer (area A) of fluid at depth h below the free surface. The weight of the column of liquid above it is $\rho A h g$. If P_0 is the pressure at the surface (atmospheric pressure), equilibrium of the column gives:

$$P = P_0 + \rho g h$$

- **Absolute pressure** $P = P_0 + \rho g h$. **Gauge pressure** = $P - P_0 = \rho g h$.
- Pressure at a point depends only on the depth and the density of the fluid, not on the shape of the container (hydrostatic paradox).
- All points at the same horizontal level in a connected fluid at rest have the same pressure.

Measuring pressure

- **Mercury barometer:** A glass tube filled with mercury is inverted in a mercury trough. Mercury falls until the pressure of the column $\rho g h$ balances the atmospheric pressure: $P_0 = \rho g h$. Standard height $h = 0.76$ m (76 cm) gives $P_0 = 13600 \times 9.8 \times 0.76 \approx 1.013 \times 10^5$ Pa.
- **Open-tube manometer:** A U-tube containing liquid is connected to the vessel at one end and open to the atmosphere at the other. The gauge pressure is $P - P_0 = \rho g h$, where h is the difference in liquid levels.

- **Others:** Bourdon gauge (for high pressures), aneroid barometer (no liquid), sphygmomanometer (blood pressure).

Solved Numerical 4

Q. Find the absolute pressure at a depth of 10 m in water ($P_0 = 1.013 \times 10^5 \text{ Pa}$).

Sol. $P = P_0 + \rho g h = 1.013 \times 10^5 + 1000 \times 9.8 \times 10 = 1.013 \times 10^5 + 0.98 \times 10^5 \approx \mathbf{1.99 \times 10^5 \text{ Pa}}$ (about 2 atm).

2.2 Pascal's Principle and Hydraulics

Pascal's law

A change in the pressure applied to an enclosed incompressible fluid is transmitted undiminished to every portion of the fluid and to the walls of the containing vessel.

Hydraulic lift (hydraulic press)

It consists of two cylinders of different cross-sectional areas A_1 (small) and A_2 (large), connected by a pipe and filled with an incompressible liquid, each fitted with a piston. A small force F_1 is applied on the small piston. The pressure $P = F_1 / A_1$ is transmitted undiminished to the large piston, which therefore exerts a force

$$F_2 = P A_2 = F_1 (A_2 / A_1)$$

Since $A_2 > A_1$ the output force is larger than the input force. The **mechanical advantage** is A_2 / A_1 .

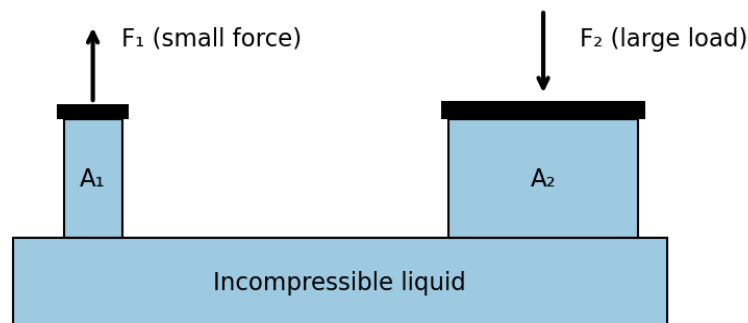


Fig. 2.1: Hydraulic lift based on Pascal's principle

Conservation of energy: When the small piston moves down by d_1 , the large piston rises by d_2 such that $A_1 d_1 = A_2 d_2$ (volume of liquid conserved). Work done: $F_1 d_1 = F_2 d_2$ — the force is multiplied but the distance moved is reduced in the same ratio; no energy is gained.

Applications: hydraulic jacks, car lifts, hydraulic brakes, excavators, hydraulic press, dental chairs and aircraft landing gear.

Solved Numerical 5

Q. In a hydraulic lift the pistons have areas 10 cm^2 and 500 cm^2 . What force must be applied to lift a 2000 kg car? ($g = 9.8 \text{ m/s}^2$)

Sol. $F_2 = 2000 \times 9.8 = 19600 \text{ N}$. $F_1 = F_2 (A_1/A_2) = 19600 \times (10/500) = \mathbf{392 \text{ N}}$.

2.3 Archimedes' Principle and Buoyancy

Archimedes' principle

When a body is wholly or partly immersed in a fluid, it experiences an upward force (buoyant force) equal to the weight of the fluid displaced by it.

$$F_B = \rho_f V_d g$$

where ρ_f is the density of the fluid and V_d the volume of fluid displaced. **Proof:** Imagine the displaced fluid replaced by an equal volume of the same fluid. It is in equilibrium, so the net upward force from the surrounding fluid equals its weight $\rho_f V_d g$. The same force acts on the immersed body, since the surrounding pressure distribution is unchanged. The line of action passes through the centre of buoyancy (centroid of the displaced fluid).

Conditions for floating and sinking

Condition	Result
Weight of body > buoyant force ($\rho_{\text{body}} > \rho_{\text{fluid}}$)	Body sinks
Weight of body = buoyant force ($\rho_{\text{body}} = \rho_{\text{fluid}}$)	Body floats fully submerged (neutral buoyancy)
Weight of body < buoyant force ($\rho_{\text{body}} < \rho_{\text{fluid}}$)	Body rises and floats partially submerged

For a floating body, the fraction submerged is $V_d / V = \rho_{\text{body}} / \rho_{\text{fluid}}$. **Apparent weight** of an immersed body = true weight – buoyant force. This also gives the **relative density** of a solid: $RD = \text{weight in air} / (\text{weight in air} - \text{weight in water})$.

Applications

- A steel ship floats because its hollow shape displaces a large volume of water, with weight of displaced water equal to the weight of the ship.
- Submarines control depth by taking in or expelling water in ballast tanks; hot-air balloons and airships rise since displaced air weighs more than the balloon.
- Hydrometer measures the density of liquids; the Plimsoll line on ships marks safe loading in different waters; icebergs float with about 90% of their volume under water ($\rho_{\text{ice}} \approx 920 \text{ kg/m}^3$).

Solved Numerical 6

Q. A block of mass 0.5 kg and volume $2 \times 10^{-4} \text{ m}^3$ is fully immersed in water. Will it sink? Find the buoyant force.

Sol. $F_B = \rho V g = 1000 \times 2 \times 10^{-4} \times 9.8 = 1.96 \text{ N}$; weight = $0.5 \times 9.8 = 4.9 \text{ N} > F_B$, so the block **sinks** (density $2500 \text{ kg/m}^3 > 1000 \text{ kg/m}^3$).

2.4 Fluid Dynamics: Streamline Flow, Bernoulli's Equation, Viscosity

Ideal fluid and streamline flow

An **ideal fluid** is incompressible, non-viscous and its flow is steady (the velocity at a point does not change with time) and irrotational. In **streamline (laminar) flow** each fluid particle follows a definite path called a streamline; the tangent at any point gives the direction of velocity, and two streamlines never cross.

Equation of continuity

Consider steady flow through a tube with cross-sections A_1 and A_2 where the speeds are v_1 and v_2 . In time Δt , the mass flowing through section 1 is $\rho A_1 v_1 \Delta t$, which must equal the mass leaving through section 2 (no accumulation):

$$A_1 v_1 = A_2 v_2 = \text{constant}$$

Fluid speeds up in narrow sections (e.g., water from a nozzle, a river at a narrow channel) and slows down where the tube widens.

Bernoulli's equation (principle of conservation of energy)

Statement

For the steady, streamline, non-viscous flow of an incompressible fluid, the sum of the pressure energy, kinetic energy and potential energy per unit volume remains constant along a streamline.

$$P + \frac{1}{2} \rho v^2 + \rho g h = \text{constant}$$

Derivation: Let fluid flow through a tube whose section 1 (area A_1) is at height h_1 with speed v_1 and pressure P_1 , and section 2 (area A_2) is at height h_2 , speed v_2 , pressure P_2 . In a short time Δt , a volume $\Delta V = A_1 v_1 \Delta t = A_2 v_2 \Delta t$ (continuity) enters at 1 and leaves at 2. Work done on the fluid by the pressure forces:

$$W = P_1 A_1 (v_1 \Delta t) - P_2 A_2 (v_2 \Delta t) = (P_1 - P_2) \Delta V$$

Change in kinetic energy: $\Delta K = \frac{1}{2} \rho \Delta V (v_2^2 - v_1^2)$. Change in potential energy: $\Delta U = \rho \Delta V g (h_2 - h_1)$. By the work-energy theorem, $W = \Delta K + \Delta U$:

$$(P_1 - P_2) = \frac{1}{2} \rho (v_2^2 - v_1^2) + \rho g (h_2 - h_1)$$

$$P_1 + \frac{1}{2} \rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho g h_2$$

Since sections 1 and 2 are arbitrary, $P + \frac{1}{2} \rho v^2 + \rho g h$ is constant. For horizontal flow (h same) the equation reduces to $P + \frac{1}{2} \rho v^2 = \text{constant}$: **where speed is high, pressure is low.**

Applications of Bernoulli's principle

- **Torricelli's theorem:** speed of efflux from a hole at depth h below the free surface of a liquid is $v = \sqrt{2gh}$.
- **Venturi meter:** measures flow speed in a pipe from the pressure difference between a wide and a narrow section: $v_1 = A_2 \sqrt{2\Delta P / \rho (A_1^2 - A_2^2)}$.
- **Aerofoil lift:** air moves faster over the curved upper surface of an aircraft wing, giving lower pressure above than below, hence upward lift.
- **Atomizers, spray guns, Bunsen burner and carburettor:** fast air stream lowers pressure and sucks liquid/gas.
- Why a roof may blow off in a storm; why two passing trucks or ships are drawn towards each other.

Viscosity

Viscosity is the property of a fluid by which it opposes relative motion between its adjacent layers. It arises from internal friction (momentum exchange between layers). Consider a fluid between a fixed plate and a moving plate of area A separated by distance dx ; the velocity changes by dv . Newton's law of viscous flow:

$$F = \eta A (dv/dx)$$

where dv/dx is the **velocity gradient** and η the **coefficient of viscosity**. SI unit: pascal-second (Pa·s) or N s m^{-2} ; CGS unit: poise (1 poise = 0.1 Pa·s). Dimensions $[M L^{-1} T^{-1}]$. Viscosity of liquids decreases with increase in temperature, while that of gases increases with temperature.

Stokes' law and terminal velocity

A small sphere of radius r moving slowly with velocity v through a fluid of viscosity η experiences a viscous drag $F = 6\pi \eta r v$. A sphere (density ρ) falling through a fluid (density σ) accelerates until the net force is zero: weight = buoyancy + drag, giving the **terminal velocity**

$$v_t = \frac{2r^2(\rho - \sigma)g}{9\eta}$$

This explains why raindrops fall at constant speed, and the method is used to determine η of liquids (falling-sphere viscometer).

Streamline versus turbulent flow – Reynolds number

Flow is streamline when speed is low; above a critical speed it becomes turbulent with eddies. The Reynolds number is $Re = \rho v D / \eta$. Roughly, $Re < 2000$: laminar; $Re > 3000$: turbulent; between: unstable.

Solved Numerical 7

Q. Water flows at 2 m/s in a pipe of diameter 4 cm that narrows to diameter 2 cm. Find the speed in the narrow part.

Sol. $A_1 v_1 = A_2 v_2 \Rightarrow v_2 = v_1 (d_1/d_2)^2 = 2 \times (4/2)^2 = 8 \text{ m/s}$.

Quick revision – Unit II

- $P = P_0 + \rho gh$; pressure is the same at the same level in a connected fluid at rest.
- Pascal: pressure is transmitted undiminished; hydraulic lift multiplies force by A_2/A_1 but not work.
- Archimedes: $F_B = \text{weight of fluid displaced}$; floats if $\rho_{\text{body}} < \rho_{\text{fluid}}$.
- Continuity: $A v = \text{constant}$. Bernoulli: $P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant}$ (conservation of energy).
- Viscosity: $F = \eta A dv/dx$; liquids become less viscous on heating, gases more viscous.
- Stokes: $F = 6\pi\eta r v$; terminal velocity $v_t = 2r^2(\rho - \sigma)g / 9\eta$.

Solved Numerical 7A

Q. Water leaks from a hole 5 m below the free surface of a tank. Find the speed of efflux ($g = 9.8 \text{ m/s}^2$).

Sol. $v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 5} = \sqrt{98} \approx 9.9 \text{ m/s}$.

Solved Numerical 7B

Q. A piece of wood floats in water with 60% of its volume submerged. Find the density of wood.

Sol. Fraction submerged = $\rho_{\text{wood}} / \rho_{\text{water}} = 0.6 \Rightarrow \rho_{\text{wood}} = 600 \text{ kg/m}^3$.

Frequently asked 2.5-mark questions (with answers)

Question	Answer
Why does a ship made of steel float?	Because its hollow shape displaces water whose weight equals the ship's weight; its average density is less than water.
Why do raindrops fall with constant speed?	They reach terminal velocity when weight = buoyancy + viscous drag.
Why is it easier to float in sea water?	Sea water has higher density, so for the same displaced volume the buoyant force is larger.
What happens to pressure when speed increases (horizontal flow)?	Pressure decreases (Bernoulli's principle).

Short answer questions – Unit II

1. State Pascal's law and mention two applications.
2. State and prove Archimedes' principle.
3. What is streamline flow? State the equation of continuity.
4. Derive Bernoulli's equation.

5. State Stokes' law. What is terminal velocity?

UNIT III: SOUND

3.1 Introduction: Origin of Sound; Types of Sound Waves

Sound is produced by vibrating bodies (tuning fork, string, vocal cords, drum membrane). The vibrating body disturbs the surrounding medium, creating alternate **compressions** (regions of higher pressure/density) and **rarefactions** (regions of lower pressure/density) that travel outward. Sound is a **longitudinal mechanical wave**: the particles of the medium oscillate parallel to the direction of propagation, so it needs a material medium and cannot travel through vacuum.

A wave is characterised by frequency f , wavelength λ and speed v related by:

$$v = f\lambda$$

Classification of sound waves based on frequency

Type	Frequency range	Examples / Uses
Infrasonic	Below 20 Hz	Earthquakes, volcanoes, elephants & whales communication; seismology
Audible (sonic)	20 Hz – 20,000 Hz	Human speech, music — range audible to the human ear
Ultrasonic	Above 20,000 Hz	Bats, dolphins; SONAR, ultrasound imaging, cleaning, flaw detection

Characteristics of musical sound

- **Pitch**: the sensation of a high or low sound; depends on frequency.
- **Loudness**: depends on intensity (amplitude²) and sensitivity of the ear.
- **Quality (timbre)**: enables us to distinguish two sounds of the same pitch and loudness; depends on the number and strength of overtones (waveform).

3.2 Velocity of Sound in Air and Water

The speed of a mechanical wave depends on the elastic and inertial properties of the medium. In general:

$$v = \sqrt{\text{elasticity} / \text{density}}$$

Medium	Formula	Symbols
Solid rod	$v = \sqrt{Y / \rho}$	Y = Young's modulus
Liquid	$v = \sqrt{K / \rho}$	K = bulk modulus of the liquid
Gas	$v = \sqrt{\gamma P / \rho}$	$\gamma = C_p / C_v$, P = pressure

In air: $v \approx 332$ m/s at 0 °C and ≈ 343 m/s at 20 °C. **In water:** with $K = 2.2 \times 10^9$ Pa and $\rho = 1000$ kg/m³, $v = \sqrt{(2.2 \times 10^9 / 1000)} \approx 1480$ m/s — roughly four times faster than in air, as water is much less compressible (larger K) even though it is denser.

Medium	Approx. speed (m/s)
Air (0 °C)	332
Air (20 °C)	343
Hydrogen (0 °C)	1284
Water (25 °C)	1493
Sea water	1530
Steel	5000

Speed of sound is generally greatest in solids, less in liquids, least in gases. It is independent of frequency and amplitude (for ordinary sounds), so different notes from an orchestra reach the listener together.

3.3 Newton's Formula for Velocity of Sound

Newton assumed that when a sound wave passes through a gas, the compressions and rarefactions occur so slowly that heat has time to flow, so the temperature remains constant: the process is **isothermal**. For an isothermal change $PV = \text{constant}$, hence the bulk modulus $K = P$ (the pressure itself). Therefore:

$$v = \sqrt{K/\rho} = \sqrt{P/\rho} \quad (\text{Newton's formula})$$

Check for air at NTP: $P = 1.013 \times 10^5 \text{ N/m}^2$, $\rho = 1.293 \text{ kg/m}^3$:

$$v = \sqrt{(1.013 \times 10^5 / 1.293)} \approx 280 \text{ m/s}$$

But the experimentally measured value is about 332 m/s. The 52 m/s ($\approx 16\%$) discrepancy showed that Newton's assumption was wrong.

3.4 Laplace Correction

Laplace (1816) pointed out that the compressions and rarefactions in a sound wave follow each other so rapidly (hundreds of times per second) and air is a poor conductor of heat, so heat cannot flow out of the compressed layers or into the rarefied layers. Hence the changes are **adiabatic**, not isothermal. For an adiabatic change $PV^\gamma = \text{constant}$, so the bulk modulus is $K = \gamma P$. Therefore:

$$v = \sqrt{(\gamma P / \rho)} \quad (\text{Newton-Laplace formula})$$

For air $\gamma = 1.4$:

$$v = \sqrt{1.4 \times 280} = 1.183 \times 280 \approx 331.3 \text{ m/s}$$

which agrees closely with the experimental value of 332 m/s. Thus Laplace's correction removes the discrepancy. Therefore, the correct factor is $\sqrt{\gamma}$: $v_{\text{Laplace}} = \sqrt{\gamma} \cdot v_{\text{Newton}}$.

Comparison

- Newton: isothermal, $K = P$, $v = \sqrt{P/\rho} = 280 \text{ m/s}$ (disagrees with experiment).
- Laplace: adiabatic, $K = \gamma P$, $v = \sqrt{\gamma P/\rho} = 331.3 \text{ m/s}$ (agrees with experiment).
- $\gamma = 1.67$ for monoatomic, 1.40 for diatomic (air), 1.33 for triatomic gases.

Solved Numerical 8

Q. Calculate the velocity of sound in hydrogen at NTP if $\gamma = 1.4$ and density of hydrogen is 0.09 kg/m^3 .

Sol. $v = \sqrt{\gamma P / \rho} = \sqrt{(1.4 \times 1.013 \times 10^5 / 0.09)} = \sqrt{(1.576 \times 10^6)} \approx \mathbf{1255 \text{ m/s}}$.

3.5 Sound Intensity

The **intensity** of sound at a point is the amount of sound energy passing per second normally through unit area at that point (power per unit area):

$$I = P / A \quad (SI \text{ unit: } W/m^2)$$

For a plane progressive wave of frequency f and amplitude a in a medium of density ρ with wave speed v :

$$I = 2 \pi^2 f^2 a^2 \rho v \Rightarrow I \propto a^2, I \propto f^2$$

For a point source of power P radiating uniformly in all directions, $I = P / 4\pi r^2$. This is the **inverse-square law**: doubling the distance cuts the intensity to one-fourth.

Intensity level – the decibel scale

Human ears respond to an enormous range of intensities, from the threshold of hearing $I_0 = 10^{-12} \text{ W/m}^2$ to the threshold of pain $\approx 1 \text{ W/m}^2$. A logarithmic scale is therefore used. The **sound intensity level** is defined as:

$$\beta = 10 \log_{10} (I / I_0) \text{ decibel (dB)}$$

Sound	Intensity level (dB)
Threshold of hearing	0
Whisper	20
Normal conversation	60
Heavy traffic	80
Rock concert / siren	110–120
Threshold of pain	120–130

A change of 10 dB corresponds to a tenfold change in intensity; 3 dB corresponds to doubling the intensity. **Loudness** is the subjective sensation and depends on both intensity and the frequency response of the ear (measured in phons/sones).

Solved Numerical 9

Q. Find the intensity level in dB of a sound of intensity 10^{-6} W/m^2 .

Sol. $\beta = 10 \log_{10}(10^{-6} / 10^{-12}) = 10 \log_{10}(10^6) = \mathbf{60 \text{ dB}}$ (normal conversation).

3.6 Effect of Temperature, Pressure and Humidity on the Velocity of Sound

(a) Effect of temperature

For a gas $\rho = M P / (R T)$, so $v = \sqrt{\gamma R T / M} \Rightarrow v \propto \sqrt{T}$ (T in kelvin). If v_0 and v_t are speeds at 0°C and $t^\circ\text{C}$:

$$v_t / v_0 = \sqrt{T / T_0} = \sqrt{(1 + t/273)} \approx 1 + t/546$$

Thus, $v_t \approx v_0 + 0.61 t \text{ m/s}$; the speed of sound in air increases by about **0.61 m/s for every 1°C** rise in temperature. This is why sound travels faster on a hot day.

(b) Effect of pressure

At constant temperature, by Boyle's law $P/\rho = \text{constant}$, so $v = \sqrt{\gamma P/\rho}$ is unchanged when the pressure changes: **the velocity of sound is independent of pressure** (provided temperature is constant). Both P and ρ change in the same ratio. This is why the speed of sound is the same at the foot of a mountain and at its top if the temperature is the same.

(c) Effect of humidity

Water vapour is lighter than dry air (density of vapour $\approx 5/8$ that of dry air). Moist air is therefore less dense than dry air at the same temperature and pressure, giving a smaller ρ ; the effective γ changes only slightly. Hence **velocity of sound increases with humidity**. Sound travels faster in damp air than in dry air (which is also why sound is heard better and farther before rain).

Summary

- Temperature: $v \propto \sqrt{T}$ — increases with temperature ($\approx 0.61 \text{ m/s per } ^\circ\text{C}$).
- Pressure: no effect (at constant temperature).
- Humidity: increases with humidity.
- Wind: wind in the direction of propagation increases the effective speed; opposite wind reduces it.
- Frequency, wavelength change: no effect on speed in air (no dispersion).

Solved Numerical 10

Q. The speed of sound in air at 0°C is 332 m/s . Find its speed at 27°C .

Sol. $v_{27} = 332 \times \sqrt{(300/273)} = 332 \times 1.048 \approx \mathbf{348 \text{ m/s}}$ (approximation: $332 + 0.61 \times 27 \approx 348.5 \text{ m/s}$).

Solved Numerical 11 (Echo)

Q. A person hears an echo 3 s after shouting towards a cliff. If $v = 340 \text{ m/s}$, find the distance of the cliff.

Sol. Sound travels to the cliff and back: $2d = v t \Rightarrow d = 340 \times 3 / 2 = \mathbf{510 \text{ m}}$.

Quick revision – Unit III

- Sound = longitudinal mechanical wave; needs a medium; $v = f\lambda$.
- Infrasonic < 20 Hz; audible 20 Hz–20 kHz; ultrasonic > 20 kHz.
- Newton (isothermal): $v = \sqrt{P/\rho} = 280 \text{ m/s}$; Laplace (adiabatic): $v = \sqrt{\gamma P/\rho} = 331.3 \text{ m/s}$.
- Intensity $I = P/A$; level $\beta = 10 \log(I/I_0) \text{ dB}$; $I_0 = 10^{-12} \text{ W/m}^2$.
- $v \propto \sqrt{T}$ (about +0.61 m/s per °C); independent of pressure; increases with humidity.

Solved Numerical 11A

Q. Sound of frequency 512 Hz travels in air at 340 m/s. Find its wavelength.

Sol. $\lambda = v / f = 340 / 512 \approx \mathbf{0.664 \text{ m}}$.

Solved Numerical 11B

Q. The intensity of a sound at 2 m from a point source is 0.08 W/m^2 . Find the intensity at 4 m.

Sol. $I \propto 1/r^2 \Rightarrow I_2 = 0.08 \times (2/4)^2 = \mathbf{0.02 \text{ W/m}^2}$.

Frequently asked 2.5-mark questions (with answers)

Question	Answer
Why can sound not travel in vacuum?	It is a mechanical wave and requires a material medium for compressions and rarefactions.
Why is sound faster in water than in air?	Water has a much larger bulk modulus (elasticity) which outweighs its higher density.
Why is Newton's assumption wrong?	Compressions and rarefactions occur too rapidly and air is a poor conductor, so changes are adiabatic, not isothermal.
Why do we hear distant sounds better on a humid day or at night?	Humid air is less dense so sound travels faster; temperature gradients also bend sound waves downward at night.

Short answer questions – Unit III

1. What are infrasonic, audible and ultrasonic waves?
2. State Newton's formula for the speed of sound and explain why it fails.
3. What is Laplace's correction? Derive the corrected formula.
4. Define intensity of sound and the decibel.
5. How does temperature affect the speed of sound in air? Does pressure change it?

UNIT IV: SEMICONDUCTOR PHYSICS

4.1 Introduction; Intrinsic Semiconductors

On the basis of electrical conductivity, solids are classified as conductors (metals), insulators and semiconductors. The classification is explained by the **energy band theory**: the valence band (VB) is the highest band filled with electrons at 0 K, the conduction band (CB) is the next higher band, and the gap between them is the **forbidden energy gap** E_g .

Property	Conductor	Semiconductor	Insulator
Energy gap E_g	Nil (bands overlap)	Small (< 3 eV)	Large (> 3 eV)
Resistivity (Ω m)	$10^{-8} - 10^{-6}$	$10^{-5} - 10^6$	$> 10^8$
Effect of temperature	Resistance increases	Resistance decreases	Resistance decreases (slightly)
Examples	Cu, Ag, Al	Si (1.1 eV), Ge (0.67 eV)	Diamond, glass, mica

Intrinsic semiconductor

A pure semiconductor with no impurity (e.g., pure silicon or germanium) is called intrinsic. Each atom has four valence electrons forming covalent bonds with four neighbours. At 0 K all bonds are intact and it behaves as an insulator. At room temperature, thermal energy breaks some bonds: an electron jumps to the conduction band leaving a vacancy called a **hole** in the valence band. Thus electron–hole pairs are generated:

$$n = p = n_i$$

- The hole behaves as a positive charge carrier; an electron from a neighbouring bond fills it, so the hole moves in the opposite direction to the electrons.
- Total current = electron current + hole current. Conductivity: $\sigma = e (n \mu_e + p \mu_h)$.
- The carrier concentration n_i increases rapidly with temperature, so the resistance of a semiconductor falls with temperature (negative temperature coefficient).
- The Fermi level of an intrinsic semiconductor lies near the middle of the forbidden gap.

4.2 Extrinsic Semiconductors: P-type and N-type

The conductivity of an intrinsic semiconductor is low. It is greatly increased by adding a small amount (about 1 part in 10^6 to 10^8) of a suitable impurity — a process called **doping**. The doped semiconductor is called **extrinsic**.

N-type semiconductor

Doping with a **pentavalent** impurity (5 valence electrons: phosphorus, arsenic, antimony) gives an N-type semiconductor. Four electrons of the impurity atom form covalent bonds; the fifth is loosely

bound and is easily released into the conduction band at room temperature. The impurity atom, which donates an electron, is called a **donor** and becomes a positive ion. Electrons are the **majority carriers** and holes the minority carriers. The donor level lies just below the conduction band; the Fermi level shifts upward, close to the conduction band.

P-type semiconductor

Doping with a **trivalent** impurity (3 valence electrons: boron, aluminium, gallium, indium) gives a P-type semiconductor. The impurity atom forms only three covalent bonds, leaving one bond incomplete — a hole. It accepts an electron from a neighbouring bond and is called an **acceptor**, becoming a negative ion. Holes are the **majority carriers** and electrons the minority carriers. The acceptor level lies just above the valence band; the Fermi level shifts downward, close to the valence band.

Law of mass action

In thermal equilibrium, for any semiconductor: $n p = n_i^2$. Doping with donors increases n and, proportionally, reduces p . Note that both N-type and P-type semiconductors are **electrically neutral** overall.

Feature	N-type	P-type
Impurity	Pentavalent (P, As, Sb) – donor	Trivalent (B, Al, Ga, In) – acceptor
Majority carriers	Electrons	Holes
Minority carriers	Holes	Electrons
Impurity ion formed	Positive donor ion	Negative acceptor ion
Fermi level	Near conduction band	Near valence band
Conduction mainly by	Free electrons	Holes

4.3 P-N Junction Diode and its V-I Characteristics

A **P-N junction** is formed when a P-type and an N-type semiconductor are joined in one single crystal. Electrons from the N-side diffuse across the junction into the P-side, and holes from the P-side diffuse into the N-side. They recombine near the junction, leaving behind immobile positive donor ions on the N-side and negative acceptor ions on the P-side. This region devoid of free carriers is the **depletion layer** (about 1 μm thick). The resulting internal electric field produces a **barrier potential** (about 0.7 V for silicon and 0.3 V for germanium), which stops further diffusion.

Forward bias

The P-side is connected to the positive terminal and N-side to the negative terminal of the battery. The external field opposes the junction field, the depletion layer narrows and the barrier is lowered. When the applied voltage exceeds the **knee (cut-in) voltage** (≈ 0.7 V for Si; 0.3 V for Ge), the current rises rapidly (mA range) because majority carriers cross the junction.

Reverse bias

The P-side is connected to the negative terminal and the N-side to the positive terminal. The external field adds to the junction field, the depletion layer widens and the barrier increases. Only a very small **reverse saturation current** (μA for Ge, nA for Si) flows, due to minority carriers. It is nearly independent of the reverse voltage until the **breakdown voltage** is reached, after which the current increases sharply.

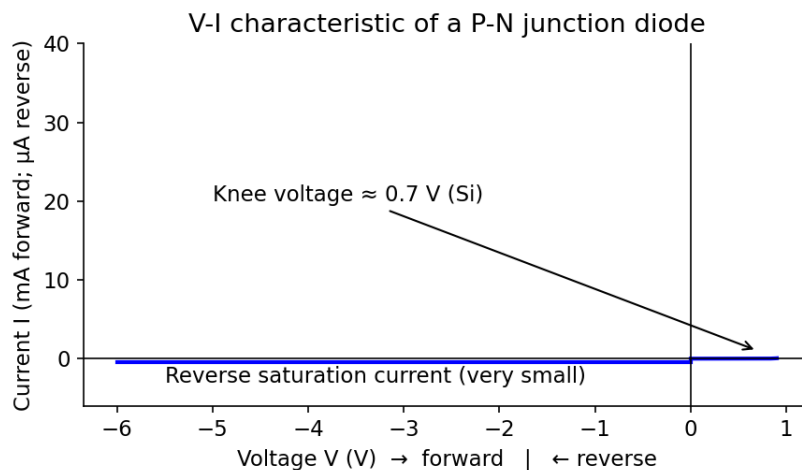


Fig. 4.1: V-I characteristic of a P-N junction diode

Diode equation: $I = I_0 (e^{(eV / \eta kT)} - 1)$, where I_0 is the reverse saturation current and $\eta = 1$ (Ge) or ≈ 2 (Si). **Dynamic (a.c.) resistance:** $r = \Delta V / \Delta I$. The diode conducts easily in forward bias and almost not at all in reverse bias, so it works as a one-way valve (rectifier).

Parameter	Silicon	Germanium
Barrier potential	0.7 V	0.3 V
Knee voltage	≈ 0.7 V	≈ 0.3 V
Reverse saturation current	nA range	μA range
Max operating temperature	≈ 175 °C	≈ 75 °C

Applications: half-wave and full-wave rectifiers, clippers/clampers, signal detectors in radios, voltage multipliers and logic gates.

4.4 Zener Diode and Voltage Regulation

A **Zener diode** is a specially designed P-N junction diode that is heavily doped, so it has a very thin depletion layer. It is operated in the reverse-biased condition in the breakdown region without being damaged. Its symbol resembles an ordinary diode with bent ends on the cathode bar.

Reverse breakdown mechanisms

- **Zener breakdown ($V_z < \text{about } 5 \text{ V}$):** In a heavily doped junction the depletion layer is extremely thin, so even a modest reverse voltage produces a very strong electric field ($> 10^6 \text{ V/m}$) that directly pulls electrons out of covalent bonds (field ionisation), causing a large current.
- **Avalanche breakdown ($V_z > \text{about } 6 \text{ V}$):** In lightly doped junctions with wider depletion layers, minority carriers accelerated by the field collide with atoms and release more carriers, causing a cumulative (avalanche) multiplication of current.

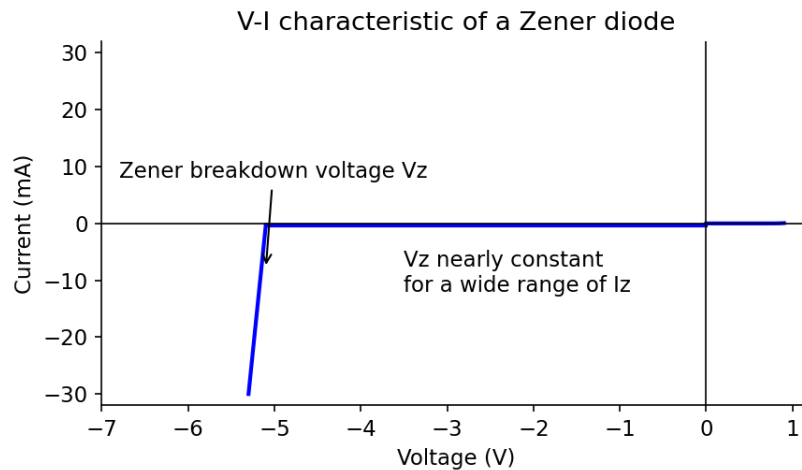


Fig. 4.2: V-I characteristic of a Zener diode

In forward bias, the Zener diode behaves like an ordinary diode. In reverse bias, the current is very small until the **Zener voltage V_z** is reached; then the current rises steeply while the voltage across the diode stays almost constant at V_z . This property is used for voltage stabilisation.

Zener diode as a voltage regulator

The Zener diode is connected in reverse bias in parallel with the load R_L , in series with a resistor R_s that limits the current. The unregulated input voltage V_{in} ($> V_z$) is applied across the combination.

- **If the input voltage increases:** the Zener current I_z increases, so the drop across R_s increases by the same amount; the output voltage $V_{out} = V_z$ stays constant.
- **If the input voltage decreases:** I_z decreases, the drop across R_s decreases, and V_{out} remains $\approx V_z$ (provided I_z remains above the minimum).
- **If the load current changes:** I_z adjusts so that $I_s = I_z + I_L$ stays constant and V_{out} is held at V_z .

$$R_s = (V_{in} - V_z) / (I_z + I_L) \quad ; \quad V_{out} = V_z$$

Solved Numerical 12

Q. A 6 V Zener regulator is supplied from a 12 V source and feeds a load drawing 20 mA. If the Zener current is 10 mA, find R_s .

Sol. $I_s = I_z + I_L = 10 + 20 = 30 \text{ mA}$. $R_s = (12 - 6) / 30 \times 10^{-3} = \mathbf{200 \, \Omega}$.

4.5 LED (V-I Characteristics) and Photodiode

Light Emitting Diode (LED)

An LED is a forward-biased P-N junction (made from direct band-gap compound semiconductors) that emits light by **electroluminescence**. When electrons from the N-region cross the junction and recombine with holes in the P-region, they fall from the conduction band to the valence band, releasing the energy E_g as a photon of wavelength $\lambda = hc / E_g$.

Material	Colour emitted	Approx. forward voltage (V)
GaAs	Infrared	1.2
GaAsP	Red / Orange / Yellow	1.8 – 2.2
GaP	Green	2.0 – 2.2
GaN / InGaN	Blue / White	3.0 – 3.4

- **V-I characteristics:** Similar to an ordinary diode, but the knee voltage (threshold) is higher, 1.8 V to 3.4 V depending on colour. Below the threshold no current flows and no light is emitted; above it the current rises sharply and the light intensity increases nearly proportionally to the current. In reverse bias no light is emitted; the breakdown voltage is low (≈ 5 V), so it must be protected.
- A series resistor $R = (V_s - V_F) / I_F$ (typically $I_F = 10\text{--}20$ mA) is always used to limit current.
- **Advantages:** low power consumption, long life ($> 50,000$ h), fast switching, compact, cool and mechanically rugged.
- **Uses:** indicator lamps, displays (7-segment), remote controls (IR LED), traffic signals, TV backlights, LED bulbs and optical communication.

Photodiode

A photodiode is a P-N junction diode designed to detect light. It is operated in **reverse bias** with a transparent window that allows light to fall on the depletion region. When photons of energy $h\nu \geq E_g$ strike the junction, they generate electron–hole pairs. The strong junction field sweeps electrons to the N-side and holes to the P-side, giving rise to a **photocurrent** that is proportional to the intensity of incident light.

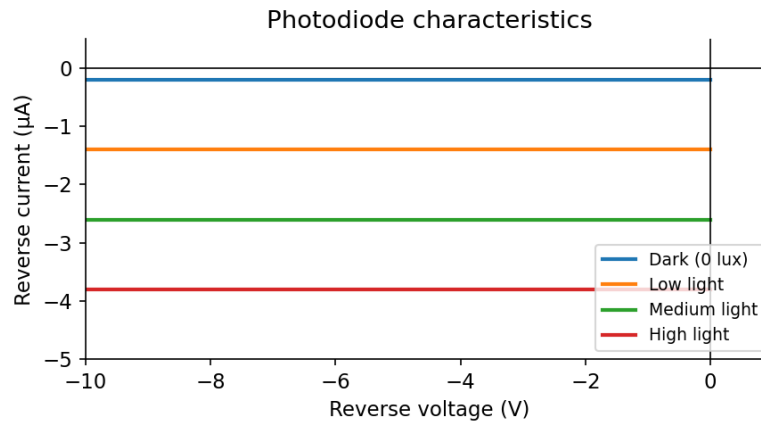


Fig. 4.3: Reverse-bias characteristics of a photodiode for different light intensities

- **Dark current:** the small reverse current that flows even when there is no light.
- **Characteristics:** In the reverse-bias region the current is nearly independent of voltage but increases linearly with illumination; at zero illumination only the dark current flows. Curves shift downward as the light intensity increases.
- **Response:** very fast (ns), high sensitivity; spectral response depends on E_g (Si: visible to near IR).
- **Uses:** optical communication receivers, remote-control sensors, light meters in cameras, burglar alarms, smoke detectors, solar-cell applications and CD/DVD pickups.

LED vs Photodiode

- LED: forward bias; converts electrical energy $\rightarrow$ light. Photodiode: reverse bias; converts light $\rightarrow$ electrical signal.
- LED is made of direct band-gap material (GaAs, GaN); photodiode typically of Si or Ge with a transparent window.

Quick revision – Unit IV

- Eg: Si 1.1 eV, Ge 0.67 eV. Resistance of semiconductors decreases with temperature.
- N-type: pentavalent donors, electrons majority. P-type: trivalent acceptors, holes majority. $np = n_i^2$.
- P-N junction: depletion layer + barrier potential (0.7 V Si, 0.3 V Ge); forward bias conducts, reverse bias blocks.
- Zener: heavily doped, works in reverse breakdown; used as voltage regulator ($R_s = (V_{in} - V_z)/(I_z + I_L)$).
- LED: forward bias, electroluminescence. Photodiode: reverse bias, light $\rightarrow$ current.

Solved Numerical 12A

Q. Find the wavelength of light emitted by an LED with band gap 1.9 eV ($h = 6.63 \times 10^{-34} \text{ J s}$, $c = 3 \times 10^8 \text{ m/s}$).

Sol. $\lambda = hc / E_g = (6.63 \times 10^{-34} \times 3 \times 10^8) / (1.9 \times 1.6 \times 10^{-19}) \approx 6.5 \times 10^{-7} \text{ m} = 654 \text{ nm}$ (red light).

Solved Numerical 12B

Q. An LED with forward voltage 2 V and current 10 mA is run from a 5 V supply. Find the series resistance.

Sol. $R = (5 - 2) / (10 \times 10^{-3}) = 300 \Omega$.

Frequently asked 2.5-mark questions (with answers)

Question	Answer
Why is a semiconductor an insulator at 0 K?	All valence electrons are in covalent bonds and the conduction band is empty, so there are no free carriers.
Is an N-type crystal negatively charged?	No, it is electrically neutral; free electrons are balanced by positive donor ions.
Why is a Zener diode heavily doped?	To obtain a very thin depletion layer so that breakdown occurs at a low, sharp voltage.
Why is a photodiode used in reverse bias?	The reverse current is very small in the dark, so the photocurrent changes are easily detected.

Short answer questions – Unit IV

1. What are intrinsic and extrinsic semiconductors?
2. Differentiate between P-type and N-type semiconductors.
3. What is a depletion layer and barrier potential?
4. Explain the working of a Zener diode as a voltage regulator.
5. What is the principle of an LED? Explain a photodiode.

Question Bank for Revision

Q.1 type – Short questions (2.5 marks each)

- State Newton's law of gravitation. / What is the value of g at the surface of the Earth?
- Define areal velocity. / State Kepler's third law. / Define escape velocity.
- Define pressure. State its SI unit. / State Pascal's law. / What is buoyancy?
- What is meant by streamline flow? / Define coefficient of viscosity.
- What are ultrasonic waves? / State Laplace's correction. / Define intensity of sound.
- What is the effect of humidity on the velocity of sound?
- What is doping? / What are majority and minority carriers? / What is breakdown voltage?
- Name two applications of LED and photodiode.

Long questions (5 marks each)

Unit	Likely questions
I	Derive Newton's law of gravitation from Kepler's law. / Show that a particle in a central force field moves in a plane with constant areal velocity. / Derive an expression for gravitational potential due to a spherical shell inside and outside. / Define gravitational field and potential and show $I = -dV/dr$.
II	State and explain Pascal's principle; explain the hydraulic lift. / Archimedes' principle; floating bodies. / Derive Bernoulli's equation and give any two applications. / What is viscosity? Derive Stokes' terminal velocity formula.
III	Derive Newton's formula; explain Laplace's correction. / Explain the effect of temperature, pressure and humidity on the velocity of sound. / Define intensity and intensity level; explain the decibel scale.
IV	Explain intrinsic and extrinsic semiconductors. / Explain the formation of the depletion layer and V-I characteristics of a P-N junction diode. / Zener diode and its use as a voltage regulator. / Explain the working and characteristics of an LED and a photodiode.

Numerical practice problems

1. Find the force of attraction between two spheres of masses 100 kg and 200 kg whose centres are 0.5 m apart. [Ans: 5.34×10^{-6} N]
2. Calculate the escape velocity from the surface of a planet of mass 6.4×10^{23} kg and radius 3.4×10^6 m. [Ans: ≈ 5.0 km/s]
3. Find the gauge pressure at a depth of 5 m in sea water ($\rho = 1030$ kg/m³). [Ans: $\approx 5.05 \times 10^4$ Pa]
4. A hydraulic press has piston radii 2 cm and 20 cm. What force on the small piston will lift a 5000 N load? [Ans: 50 N]
5. A sphere of radius 1 mm and density 8000 kg/m³ falls in glycerine ($\sigma = 1260$ kg/m³, $\eta = 0.83$ Pa s). Find the terminal velocity. [Ans: ≈ 0.0163 m/s]

6. Calculate the speed of sound in air at 40 °C using $v = 331 + 0.61 t$. [Ans: ≈ 355.4 m/s]
7. Find the intensity level of a sound that is 1000 times more intense than the threshold of hearing. [Ans: 30 dB]
8. A Zener of 5.6 V is used to regulate a 9 V supply for a load of 15 mA with $I_z = 5$ mA. Find R_s . [Ans: 170 Ω]

Glossary of Key Terms

Term	Meaning
Central force	A force directed along the line joining a particle to a fixed centre, with magnitude depending only on distance.
Areal velocity	Area swept per unit time by the radius vector, $dA/dt = L/2m$.
Gravitational potential	Work done per unit mass in bringing a body from infinity to the point.
Escape velocity	Minimum speed needed to leave a planet's gravitational field permanently (11.2 km/s for Earth).
Gauge pressure	Pressure above atmospheric pressure, pgh .
Buoyant force	Upward force on a body immersed in a fluid, equal to the weight of fluid displaced.
Viscosity	Internal friction of a fluid opposing relative motion of its layers.
Terminal velocity	Constant velocity reached when the net force on a falling body becomes zero.
Adiabatic process	A process in which no heat is exchanged with the surroundings ($PV^\gamma = \text{constant}$).
Decibel	Unit of sound intensity level, $\beta = 10 \log_{10}(I/I_0)$.
Doping	Deliberate addition of impurities to a pure semiconductor to increase conductivity.
Depletion layer	Region near a P-N junction devoid of free charge carriers.
Electroluminescence	Emission of light when current passes through a semiconductor junction (LED).

Formula Sheet

Topic	Formula
Gravitation	$F = G m_1 m_2 / r^2$; $g = GM/R^2$; $V = -GM/r$; $I = -dV/dr$; $v_e = \sqrt{2gR}$
Central force	$L = m r^2 d\theta/dt = \text{const}$; $dA/dt = L/2m$; $T^2 \propto a^3$
Fluid pressure	$P = P_0 + \rho gh$; $F_2 = F_1 (A_2/A_1)$; $F_B = \rho V g$
Fluid flow	$A_1 v_1 = A_2 v_2$; $P + \frac{1}{2} \rho v^2 + \rho gh = \text{const}$; $v = \sqrt{2gh}$; $F = \eta A dv/dx$; $F = 6\pi\eta r v$
Terminal velocity	$v_t = 2r^2(\rho - \sigma)g / 9\eta$
Sound	$v = f\lambda$; Newton: $v(P/\rho)$; Laplace: $v(\gamma P/\rho)$; $v_t \approx v_0 + 0.61t$; $\beta = 10 \log(I/I_0)$
Semiconductors	$n p = n_i^2$; $\sigma = e(n\mu_e + p\mu_h)$; $I = I_0(e^{(eV/\eta kT)} - 1)$; $R_s = (V_{in} - V_z)/(I_z + I_L)$

— *Best wishes for your examination!* —