

Class 11 Physics: Complete Formula Sheet

All 14 NCERT chapters (Part I and Part II) · CBSE syllabus 2026-27 · NCERT textbook (Reprint 2026-27)

How to use this sheet. Plain boxes cover the CBSE 2026-27 board-exam syllabus. Amber boxes marked ★ **Qualitative only** are topics the 2026-27 syllabus lists for qualitative treatment or as a statement only, so expect conceptual questions rather than derivations or numericals. Grey boxes marked ◇ **Not in 2026-27 syllabus** are in the NCERT book but not in the current syllabus. They are kept for reference and JEE/NEET. Constants: $g = 9.8 \text{ m s}^{-2}$, $G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$, $R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$, $k_B = 1.38 \times 10^{-23} \text{ J K}^{-1}$, $N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$, $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, $1 \text{ atm} = 1.01 \times 10^5 \text{ Pa}$.

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|--|------------------------------------|
| 1. Units and Measurement | 8. Mechanical Properties of Solids |
| 2. Motion in a Straight Line | 9. Mechanical Properties of Fluids |
| 3. Motion in a Plane | 10. Thermal Properties of Matter |
| 4. Laws of Motion | 11. Thermodynamics |
| 5. Work, Energy and Power | 12. Kinetic Theory |
| 6. System of Particles and Rotational Motion | 13. Oscillations |
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1 Units and Measurement

SI BASE QUANTITIES AND UNITS

Quantity	Unit	Symbol	Dimension
Length	metre	m	[L]
Mass	kilogram	kg	[M]
Time	second	s	[T]
Electric current	ampere	A	[A]
Thermodynamic temperature	kelvin	K	[K]
Amount of substance	mole	mol	[mol]
Luminous intensity	candela	cd	[cd]

COMMON DIMENSIONAL FORMULAE

- Velocity $[LT^{-1}]$; acceleration $[LT^{-2}]$
- Force $[MLT^{-2}]$; momentum, impulse $[MLT^{-1}]$
- Work, energy $[ML^2T^{-2}]$; power $[ML^2T^{-3}]$
- Pressure, stress, elastic modulus $[ML^{-1}T^{-2}]$
- Density $[ML^{-3}]$; G : $[M^{-1}L^3T^{-2}]$
- Strain, angle, refractive index: dimensionless

DIMENSIONAL ANALYSIS

- Only quantities with the same dimensions can be added, subtracted or equated
- Uses: check consistency of an equation, convert units, deduce a relation between quantities
- A dimensionally correct equation may still be wrong (dimensionless constants are missed); a dimensionally wrong one is always wrong.



SIGNIFICANT FIGURES

- All non-zero digits are significant; zeros between them are significant
- Leading zeros (0.0023) are not significant; trailing zeros after the decimal point are
- Multiply/divide: keep as many significant figures as the least precise value
- Add/subtract: keep as many decimal places as the least precise value
- Relative error = $\frac{\Delta a}{a} \times 100\%$

2 Motion in a Straight Line**VELOCITY AND ACCELERATION**

- Average velocity $\bar{v} = \frac{\Delta x}{\Delta t}$; average speed = $\frac{\text{total path length}}{\text{total time}}$
- Instantaneous: $v = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}$
- $\bar{a} = \frac{\Delta v}{\Delta t}$; $a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$
- Average speed $\geq |\text{average velocity}|$ over any interval.

GRAPHS

- Slope of x - t graph = velocity
- Slope of v - t graph = acceleration
- Area under v - t graph = displacement
- Uniform acceleration: x - t is a parabola, v - t a straight line

KINEMATIC EQUATIONS (CONSTANT a)

- $v = v_0 + at$
- $x = v_0t + \frac{1}{2}at^2$
- $v^2 = v_0^2 + 2ax$
- $x = \frac{v + v_0}{2}t$
- If the particle starts at x_0 , replace x by $x - x_0$. Free fall: $a = -g$ (upward positive).

3 Motion in a Plane**VECTORS**

- $\vec{A} = A_x\hat{i} + A_y\hat{j}$; $A_x = A \cos \theta$, $A_y = A \sin \theta$
- $A = \sqrt{A_x^2 + A_y^2}$, $\tan \theta = A_y/A_x$
- Unit vector $\hat{n} = \vec{A}/|\vec{A}|$
- $\vec{A} + \vec{B} = \vec{B} + \vec{A}$; $(\vec{A} + \vec{B}) + \vec{C} = \vec{A} + (\vec{B} + \vec{C})$
- $\vec{A} - \vec{B} = \vec{A} + (-\vec{B})$

ADDITION OF TWO VECTORS

- Analytical: $R_x = A_x + B_x$, $R_y = A_y + B_y$
- Law of cosines:

$$R = \sqrt{A^2 + B^2 + 2AB \cos \theta}$$

- Direction: $\tan \alpha = \frac{B \sin \theta}{A + B \cos \theta}$ (angle with $\vec{A}$)



MOTION IN A PLANE

- $\vec{r} = x\hat{i} + y\hat{j}$; $\Delta\vec{r} = \Delta x\hat{i} + \Delta y\hat{j}$
- $\vec{v} = \frac{d\vec{r}}{dt} = v_x\hat{i} + v_y\hat{j}$; $\vec{a} = \frac{d\vec{v}}{dt}$
- Constant $\vec{a}$: $\vec{v} = \vec{v}_0 + \vec{a}t$, $\vec{r} = \vec{r}_0 + \vec{v}_0t + \frac{1}{2}\vec{a}t^2$
- Velocity is always tangent to the path.

PROJECTILE MOTION

- $x = (v_0 \cos \theta_0)t$, $y = (v_0 \sin \theta_0)t - \frac{1}{2}gt^2$
- Path (parabola): $y = (\tan \theta_0)x - \frac{g}{2(v_0 \cos \theta_0)^2}x^2$
- Time of flight: $T_f = \frac{2v_0 \sin \theta_0}{g}$
- Maximum height: $h_m = \frac{(v_0 \sin \theta_0)^2}{2g}$
- Range:

$$R = \frac{v_0^2 \sin 2\theta_0}{g}$$

maximum at $\theta_0 = 45^\circ$: $R_m = v_0^2/g$

UNIFORM CIRCULAR MOTION

- $v = \omega R$; $\omega = \frac{\Delta\theta}{\Delta t} = 2\pi\nu = \frac{2\pi}{T}$
- Centripetal acceleration (towards centre):

$$a_c = \frac{v^2}{R} = \omega^2 R = 4\pi^2\nu^2 R$$

4 Laws of Motion**NEWTON'S LAWS**

- First law: if net external force is zero, acceleration is zero
- Momentum $\vec{p} = m\vec{v}$
- Second law:

$$\vec{F} = \frac{d\vec{p}}{dt} = m\vec{a}$$

$$1 \text{ N} = 1 \text{ kg m s}^{-2}$$

- Third law: $\vec{F}_{AB} = -\vec{F}_{BA}$ (act on different bodies)

IMPULSE AND MOMENTUM CONSERVATION

- Impulse = $F\Delta t = \Delta p$ (change in momentum)
- Isolated system: total momentum is conserved,
 $\vec{p}_A + \vec{p}_B = \vec{p}'_A + \vec{p}'_B$
- Recoil of a gun: $m_b v_b = -M_g V_g$.

EQUILIBRIUM OF A PARTICLE

- $\vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \dots = 0$
- Componentwise: $\sum F_x = 0$, $\sum F_y = 0$, $\sum F_z = 0$

FRICTION

- Static: $f_s \leq (f_s)_{\max} = \mu_s N$
- Kinetic: $f_k = \mu_k N$, with $\mu_k < \mu_s$
- Independent of the area of contact
- Rolling friction is much smaller than sliding friction; lubricants reduce friction.

CIRCULAR MOTION

- Centripetal force $f_c = \frac{mv^2}{R}$
- Level road (friction provides f_c): $v_{\max} = \sqrt{\mu_s Rg}$
- Banked road with friction:

$$v_{\max} = \sqrt{Rg \frac{\mu_s + \tan \theta}{1 - \mu_s \tan \theta}}$$

- Optimum speed (no friction needed): $v_o = \sqrt{Rg \tan \theta}$



5 Work, Energy and Power

SCALAR PRODUCT AND WORK

- $\vec{A} \cdot \vec{B} = AB \cos \theta = A_x B_x + A_y B_y + A_z B_z$
- $\hat{i} \cdot \hat{i} = \hat{j} \cdot \hat{j} = \hat{k} \cdot \hat{k} = 1$; $\hat{i} \cdot \hat{j} = \hat{j} \cdot \hat{k} = \hat{k} \cdot \hat{i} = 0$
- Constant force: $W = \vec{F} \cdot \vec{d} = Fd \cos \theta$
- Variable force:

$$W = \int_{x_i}^{x_f} F(x) dx$$

(area under the F - x graph)

KINETIC ENERGY, WORK-ENERGY THEOREM

- $K = \frac{1}{2}mv^2 = \frac{p^2}{2m}$
- Work-energy theorem:
 $K_f - K_i = W_{net}$

POTENTIAL ENERGY AND CONSERVATION

- Conservative force: $F(x) = -\frac{dV}{dx}$; work is path-independent and zero round a closed path
- Gravitational PE near the surface: $V = mgh$
- Spring ($F = -kx$): $V = \frac{1}{2}kx^2$
- Only conservative forces acting: $K + V = \text{constant}$

POWER

- $P_{av} = \frac{W}{t}$; instantaneous $P = \frac{dW}{dt} = \vec{F} \cdot \vec{v}$
- 1 hp = 746 W; 1 kWh = 3.6×10^6 J

COLLISIONS

- Momentum is conserved in every collision; KE is conserved only in an elastic collision
- Completely inelastic (bodies stick): $v = \frac{m_1 v_{1i}}{m_1 + m_2}$ (m_2 at rest), KE lost = $\frac{1}{2} \frac{m_1 m_2}{m_1 + m_2} v_{1i}^2$
- Elastic, 1D (m_2 at rest):

$$v_{1f} = \frac{(m_1 - m_2)}{m_1 + m_2} v_{1i}, \quad v_{2f} = \frac{2m_1}{m_1 + m_2} v_{1i}$$

- Equal masses in an elastic head-on collision exchange velocities. In 2D, apply momentum conservation along x and y separately.

6 System of Particles and Rotational Motion

CENTRE OF MASS

- Two particles on a line: $X = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}$
- n particles:

$$\vec{R} = \frac{\sum m_i \vec{r}_i}{M}$$

- Rigid body: $X = \frac{1}{M} \int x dm$; uniform rod: CM at its centre
- $\vec{V} = \vec{P}/M$; $M\vec{A} = \vec{F}_{ext}$
- If $\vec{F}_{ext} = 0$, total linear momentum is constant and the CM moves uniformly.

VECTOR PRODUCT

- $|\vec{a} \times \vec{b}| = ab \sin \theta$, direction by the right-hand rule
- $\vec{a} \times \vec{b} = -\vec{b} \times \vec{a}$; $\vec{a} \times \vec{a} = 0$
- $\hat{i} \times \hat{j} = \hat{k}$, $\hat{j} \times \hat{k} = \hat{i}$, $\hat{k} \times \hat{i} = \hat{j}$



ANGULAR KINEMATICS

- $\omega = \frac{d\theta}{dt}$, $\vec{v} = \vec{\omega} \times \vec{r}$, $v = \omega r$
- $\alpha = \frac{d\omega}{dt}$
- Constant α : $\omega = \omega_0 + \alpha t$; $\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$;
 $\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$

EQUILIBRIUM OF A RIGID BODY

- Translational: $\sum \vec{F}_i = 0$
- Rotational: $\sum \vec{\tau}_i = 0$
- Principle of moments (lever): load arm $\times$ load = effort arm $\times$ effort
- Mechanical advantage = $\frac{F_1}{F_2} = \frac{d_2}{d_1}$
- Couple: equal, opposite forces with different lines of action; net force zero, net torque non-zero

TORQUE AND ANGULAR MOMENTUM

- Torque $\vec{\tau} = \vec{r} \times \vec{F}$, $\tau = rF \sin \theta$
- Angular momentum $\vec{l} = \vec{r} \times \vec{p}$, $l = rp \sin \theta$
- $\frac{d\vec{L}}{dt} = \vec{\tau}_{ext}$
- Fixed axis: $L = I\omega$
- Conservation: if $\tau_{ext} = 0$, $I\omega = \text{constant}$

ROTATIONAL DYNAMICS

- Moment of inertia $I = \sum m_i r_i^2$, SI unit kg m^2
- Radius of gyration: $I = Mk^2$
- Rotational KE = $\frac{1}{2}I\omega^2$
- $\tau = I\alpha$
- Work $W = \tau\theta$; power $P = \tau\omega$

MOMENTS OF INERTIA (VALUES ONLY, NO DERIVATION)

Body	Axis	I
Thin ring, radius R	perpendicular to plane, through centre	MR^2
Thin ring, radius R	diameter	$MR^2/2$
Thin rod, length L	perpendicular to rod, through midpoint	$ML^2/12$
Circular disc, radius R	perpendicular to disc, through centre	$MR^2/2$
Circular disc, radius R	diameter	$MR^2/4$
Hollow cylinder, radius R	axis of cylinder	MR^2
Solid cylinder, radius R	axis of cylinder	$MR^2/2$
Solid sphere, radius R	diameter	$2MR^2/5$

LINEAR VS ROTATIONAL MOTION

Linear	Rotational (fixed axis)
Displacement x , velocity v , acceleration a	θ, ω, α
Mass M	Moment of inertia I
$F = Ma$	$\tau = I\alpha$
$p = Mv$; $K = \frac{1}{2}Mv^2$	$L = I\omega$; $K = \frac{1}{2}I\omega^2$
$W = \int F ds$; $P = Fv$	$W = \int \tau d\theta$; $P = \tau\omega$



7 Gravitation

KEPLER'S LAWS

- Orbits: planets move in ellipses with the Sun at one focus
- Areas: the radius vector sweeps equal areas in equal times (angular momentum is conserved)
- Periods: $T^2 \propto a^3$; circular orbit:

$$T^2 = \frac{4\pi^2}{GM_s} R^3$$

ACCELERATION DUE TO GRAVITY

- At the surface: $g = \frac{GM_E}{R_E^2}$
- At height h : $g(h) = \frac{GM_E}{(R_E + h)^2} \approx g \left(1 - \frac{2h}{R_E}\right)$ for $h \ll R_E$
- At depth d :

$$g(d) = g \left(1 - \frac{d}{R_E}\right)$$

- g decreases with both height and depth; it is zero at the centre.

UNIVERSAL LAW OF GRAVITATION

- $F = \frac{Gm_1m_2}{r^2}$
- Superposition: $\vec{F}_R = \sum \vec{F}_i$
- Outside a uniform shell/sphere: acts as if all mass were at the centre
- Inside a uniform shell: force is zero

POTENTIAL ENERGY AND ESCAPE SPEED

- $V = -\frac{Gm_1m_2}{r}$ (zero at infinity)
- Gravitational potential = $-\frac{GM}{r}$ (PE per unit mass)
- Total energy of m near M : $E = \frac{1}{2}mv^2 - \frac{GMm}{r}$
- Escape speed:

$$v_e = \sqrt{\frac{2GM_E}{R_E}} = \sqrt{2gR_E} \approx 11.2 \text{ km s}^{-1}$$

EARTH SATELLITES

- Orbital speed at height h : $v = \sqrt{\frac{GM_E}{R_E + h}}$; close to the surface $v \approx \sqrt{gR_E}$
- Period: $T = 2\pi\sqrt{\frac{(R_E + h)^3}{GM_E}}$; near the surface $T_0 = 2\pi\sqrt{R_E/g} \approx 85 \text{ min}$
- Energy in a circular orbit of radius r :

$$K = \frac{GMm}{2r}, \quad V = -\frac{GMm}{r}, \quad E = -\frac{GMm}{2r}$$

- Total energy is negative for any bound orbit; $K = -E$ and $V = 2E$.

8 Mechanical Properties of Solids

STRESS, STRAIN, HOOKE'S LAW

- Stress = F/A ($\text{N m}^{-2} = \text{Pa}$)
- Longitudinal strain = $\Delta L/L$; volume strain = $\Delta V/V$
- Hooke's law: stress = $k \times$ strain (within the elastic limit)

YOUNG'S AND BULK MODULUS

- $Y = \frac{F/A}{\Delta L/L} = \frac{FL}{A \Delta L}$
- Bulk modulus: $B = -\frac{p}{\Delta V/V}$ (negative sign: volume decreases)
- Compressibility $k = 1/B$



★ **SHEAR MODULUS (QUALITATIVE ONLY)**

- Shear strain = $\Delta x/L = \tan \theta \approx \theta$
- $G = \frac{F/A}{\Delta x/L}$; for most materials $G \approx Y/3$
- Only solids have a shear modulus

POISSON'S RATIO AND ELASTIC ENERGY

- Poisson's ratio = $\frac{\Delta d/d}{\Delta L/L}$ (lateral strain / longitudinal strain); dimensionless
- Energy per unit volume in a stretched wire:

$$u = \frac{1}{2} \times \text{stress} \times \text{strain}$$
- Total $U = \frac{1}{2} \frac{YA(\Delta L)^2}{L}$

9 Mechanical Properties of Fluids**PRESSURE**

- $P = F/A$; 1 atm = 1.01×10^5 Pa, 1 bar = 10^5 Pa, 1 torr = 1 mm Hg = 133 Pa
- At depth h :

$$P = P_a + \rho gh$$

- Gauge pressure = $P - P_a = \rho gh$
- Pascal's law, hydraulic lift: $\frac{F_1}{A_1} = \frac{F_2}{A_2}$

STREAMLINE FLOW AND BERNOULLI

- Equation of continuity: $A_1 v_1 = A_2 v_2$ (incompressible, steady flow)
- Bernoulli:

$$P + \frac{1}{2} \rho v^2 + \rho gh = \text{constant}$$
- Torricelli's law (open tank): $v_1 = \sqrt{2gh}$
- Dynamic lift (aerofoil, spinning ball) comes from the pressure difference that Bernoulli predicts.

VISCOSITY

- $\eta = \frac{F/A}{v/l}$ (shear stress / strain rate); SI unit Pa s
- Stokes' law: $F = 6\pi\eta av$
- Terminal velocity:

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

(ρ sphere, σ fluid)

SURFACE TENSION

- $S = F/l$ = surface energy per unit area ($\text{N m}^{-1} = \text{J m}^{-2}$)
- Excess pressure in a drop or an air bubble in liquid:

$$P_i - P_o = \frac{2S}{r}$$
- Soap bubble (two surfaces): $P_i - P_o = \frac{4S}{r}$
- Capillary rise:

$$h = \frac{2S \cos \theta}{\rho ga}$$

- $\theta < 90^\circ$: liquid wets the surface and rises (water-glass).
- $\theta > 90^\circ$: it is depressed (mercury-glass).

10 Thermal Properties of Matter**TEMPERATURE SCALES AND GAS LAW**

- $t_F = \frac{9}{5}t_C + 32$
- $T = t_C + 273.15$
- Ideal gas: $PV = \mu RT$

THERMAL EXPANSION

- Linear: $\frac{\Delta l}{l} = \alpha_l \Delta T$
- Area: $\frac{\Delta A}{A} = \alpha_a \Delta T$, with $\alpha_a = 2\alpha_l$
- Volume: $\frac{\Delta V}{V} = \alpha_V \Delta T$, with

$$\alpha_V = 3\alpha_l$$
- Ideal gas at constant P : $\alpha_V = 1/T$
- Water contracts from 0°C to 4°C (anomalous expansion); it is densest at 4°C .



SPECIFIC HEAT AND CALORIMETRY

- $Q = mc \Delta T$; specific heat $s = \frac{1}{m} \frac{\Delta Q}{\Delta T}$
- Molar specific heat $C = \frac{1}{\mu} \frac{\Delta Q}{\Delta T}$; C_p at constant pressure, C_v at constant volume
- Calorimetry: heat lost = heat gained (isolated system)

CHANGE OF STATE

- Latent heat: $Q = mL$ (no change in temperature)
- Water: $L_f = 3.33 \times 10^5 \text{ J kg}^{-1}$, $L_v = 22.6 \times 10^5 \text{ J kg}^{-1}$

CONDUCTION

- Rate of heat flow through a bar:

$$H = KA \frac{T_C - T_D}{L}$$

- K = thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
- Convection needs bulk flow of a fluid; radiation needs no medium.

★ BLACKBODY RADIATION (QUALITATIVE)

- Wien's displacement law: $\lambda_m T = b$, $b = 2.9 \times 10^{-3} \text{ m K}$
- Stefan-Boltzmann law: $H = A\sigma T^4$; real body $H = eA\sigma T^4$ (e = emissivity)
- Net loss to surroundings at T_s : $H = e\sigma A(T^4 - T_s^4)$

◇ NEWTON'S LAW OF COOLING

- $-\frac{dQ}{dt} = k(T_2 - T_1)$
(T_2 body, T_1 surroundings; small differences only)

11 Thermodynamics**ZEROth AND FIRST LAWS**

- Zeroth law: A and B each in thermal equilibrium with C are in equilibrium with each other
- First law:

$$\Delta Q = \Delta U + \Delta W$$

(ΔQ supplied to the system, ΔW done by the system)

- $\Delta W = P \Delta V$; $W = \int P dV$
- U is a state variable; Q and W are not.

SPECIFIC HEATS

- Ideal gas (Mayer's relation):
 $C_p - C_v = R$
- $\gamma = C_p/C_v$
- 1 cal = 4.186 J
- Water: $s = 4186 \text{ J kg}^{-1} \text{K}^{-1}$

THERMODYNAMIC PROCESSES (IDEAL GAS)

Process	Condition	Work done by gas	First law
Isothermal	T constant, PV constant	$W = \mu RT \ln \frac{V_2}{V_1}$	$\Delta U = 0$, $Q = W$
Adiabatic	$Q = 0$, PV^γ constant	$W = \frac{\mu R(T_1 - T_2)}{\gamma - 1}$	$\Delta U = -W$
Isochoric	V constant	$W = 0$	$Q = \Delta U$
Isobaric	P constant	$W = P(V_2 - V_1) = \mu R(T_2 - T_1)$	$Q = \Delta U + W$
Cyclic	returns to initial state	area enclosed on the P - V diagram	$\Delta U = 0$, $Q = W$



SECOND LAW, REVERSIBILITY

- Kelvin-Planck: no process can absorb heat from a reservoir and convert it completely into work
- Clausius: no process can have as its sole result the transfer of heat from a colder to a hotter body
- Reversible = quasi-static and non-dissipative

◇ CARNOT ENGINE

- Two isothermal + two adiabatic reversible steps between T_1 (source) and T_2 (sink)
- $$\eta = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1}$$
- $Q_1/Q_2 = T_1/T_2$; no engine between the same two temperatures beats the Carnot engine

12 Kinetic Theory**IDEAL GAS AND GAS LAWS**

- $PV = \mu RT = k_B NT$; $k_B = R/N_A$
- Boyle's law: PV constant at fixed T
- Charles' law: V/T constant at fixed P
- Dalton's law: $P = P_1 + P_2 + \dots$ ($P_i = \mu_i RT/V$)

PRESSURE AND TEMPERATURE

- $$P = \frac{1}{3}nm\overline{v^2}$$

(n = number density)
- $PV = \frac{2}{3}E$, where $E = \frac{3}{2}k_B NT$ (translational KE)
- Mean KE per molecule: $\frac{1}{2}m\overline{v^2} = \frac{3}{2}k_B T$
- $$v_{rms} = \sqrt{\overline{v^2}} = \sqrt{\frac{3k_B T}{m}}$$

★ EQUIPARTITION (STATEMENT ONLY)

- Each translational or rotational degree of freedom carries $\frac{1}{2}k_B T$
- Each vibrational frequency carries $2 \times \frac{1}{2}k_B T = k_B T$

SPECIFIC HEATS OF GASES (FROM EQUIPARTITION)

Gas	U per mole	C_v	C_p	γ
Monatomic	$\frac{3}{2}RT$	$\frac{3}{2}R$	$\frac{5}{2}R$	$5/3$
Diatomic (rigid)	$\frac{5}{2}RT$	$\frac{5}{2}R$	$\frac{7}{2}R$	$7/5$
Diatomic (with vibration)	$\frac{7}{2}RT$	$\frac{7}{2}R$	$\frac{9}{2}R$	$9/7$
Polyatomic	$(3 + f)RT$	$(3 + f)R$	$(4 + f)R$	$\frac{4 + f}{3 + f}$

- f = number of vibrational modes of a polyatomic molecule.

MEAN FREE PATH

- $$l = \frac{1}{\sqrt{2}n\pi d^2}$$

(d = molecular diameter)

◇ SPECIFIC HEAT OF SOLIDS

- Equipartition: $C = 3R$ per mole (agrees with experiment at ordinary temperatures)



13 Oscillations

PERIODIC MOTION

- $\nu = 1/T$ ($1 \text{ Hz} = 1 \text{ s}^{-1}$)
- $\omega = \frac{2\pi}{T} = 2\pi\nu$
- SHM is the projection of uniform circular motion on a diameter.

ENERGY IN SHM

- $K = \frac{1}{2}mv^2 = \frac{1}{2}kA^2 \sin^2(\omega t + \phi)$
 - $U = \frac{1}{2}kx^2 = \frac{1}{2}kA^2 \cos^2(\omega t + \phi)$
 - Total
- $$E = K + U = \frac{1}{2}kA^2$$
- (constant without friction)

SIMPLE HARMONIC MOTION

- $x(t) = A \cos(\omega t + \phi)$
($\omega t + \phi$ = phase)
- $v(t) = -\omega A \sin(\omega t + \phi)$; max speed $v_m = \omega A$
- $a(t) = -\omega^2 A \cos(\omega t + \phi) = -\omega^2 x$; max $a_m = \omega^2 A$
- Restoring force: $F = -kx$, with $k = m\omega^2$

SPRING AND PENDULUM

- Mass on a spring: $\omega = \sqrt{\frac{k}{m}}$,
 $T = 2\pi\sqrt{\frac{m}{k}}$
- Simple pendulum (small angles):
 $T = 2\pi\sqrt{\frac{L}{g}}$
- The pendulum's period does not depend on the bob's mass or (for small swings) the amplitude.

14 Waves

PROGRESSIVE WAVE

- $y(x, t) = a \sin(kx - \omega t + \phi)$
(travels in $+x$)
- Angular wave number $k = \frac{2\pi}{\lambda}$; $\omega = \frac{2\pi}{T} = 2\pi\nu$
- Wave speed: $v = \frac{\omega}{k} = \lambda\nu = \frac{\lambda}{T}$

SPEED OF WAVES

- Stretched string (tension T , linear mass density μ):
 $v = \sqrt{\frac{T}{\mu}}$
- Fluid: $v = \sqrt{B/\rho}$; solid bar: $v = \sqrt{Y/\rho}$
- Gas: Newton $v = \sqrt{P/\rho}$; Laplace's correction $v = \sqrt{\gamma P/\rho}$

SUPERPOSITION AND REFLECTION

- $y = \sum f_i(x - vt)$
- Two waves of phase difference ϕ : $y = \left[2a \cos \frac{\phi}{2}\right] \sin\left(kx - \omega t + \frac{\phi}{2}\right)$
- $\phi = 0, 2\pi, \dots$: constructive; $\phi = \pi$: destructive
- Rigid boundary: reflected with phase change π ,
 $y_r = -a \sin(kx + \omega t)$
- Open boundary: no phase change, $y_r = a \sin(kx + \omega t)$

STANDING WAVES

- $y(x, t) = [2a \sin kx] \cos \omega t$
- Node to node (or antinode to antinode) = $\lambda/2$
- String fixed at both ends:
 $\nu_n = \frac{nv}{2L}$, $n = 1, 2, 3, \dots$



ORGAN PIPES

- Open at both ends: $\nu_n = \frac{nv}{2L}$, $n = 1, 2, 3, \dots$ (all harmonics)
- Closed at one end: $\nu = (n + \frac{1}{2}) \frac{v}{2L}$, $n = 0, 1, 2, \dots$ (odd harmonics only)
- Fundamental mode = lowest frequency = first harmonic.

BEATS

- Beat frequency:

$$\nu_{\text{beat}} = \nu_1 - \nu_2$$

- Heard when two waves of slightly different frequencies superpose

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