Physics Formula Sheet

Chapter by chapter, topic by topic. Written by the PadhoNa team for quick revision.

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CHAPTER 1

Units and Dimensions

Units and dimensional analysis

BASE QUANTITIES (SI)

$$[M],\ [L],\ [T],\ [A],\ [K],\ [\text{mol}],\ [\text{cd}]$$

COMMON DIMENSIONS

$$F : [MLT^{-2}], \qquad E : [ML^2T^{-2}], \qquad P : [ML^2T^{-3}], \qquad p : [MLT^{-1}]$$

$$G : [M^{-1}L^3T^{-2}], \qquad h : [ML^2T^{-1}], \qquad \text{pressure: } [ML^{-1}T^{-2}], \qquad \eta : [ML^{-1}T^{-1}]$$

HOMOGENEITY

$$\text{every term of a valid equation has the same dimensions}$$

CHANGING UNITS

$$n_2 = n_1\left(\frac{M_1}{M_2}\right)^a\left(\frac{L_1}{L_2}\right)^b\left(\frac{T_1}{T_2}\right)^c$$

Errors and significant figures

ABSOLUTE AND RELATIVE ERROR

$$\Delta a_{\text{mean}} = \frac{1}{n}\sum|\Delta a_i|, \qquad \text{relative error} = \frac{\Delta a}{a}$$

SUM OR DIFFERENCE

$$Z = A \pm B \ \Rightarrow\ \Delta Z = \Delta A + \Delta B$$

PRODUCT, QUOTIENT, POWER

$$Z = \frac{A^pB^q}{C^r} \ \Rightarrow\ \frac{\Delta Z}{Z} = p\frac{\Delta A}{A} + q\frac{\Delta B}{B} + r\frac{\Delta C}{C}$$

SIGNIFICANT FIGURES

$$\times, \div : \text{least number of significant figures;} \qquad +, - : \text{least number of decimal places}$$

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CHAPTER 2

Mathematics in Physics

Vectors

RESULTANT

$$R = \sqrt{A^2 + B^2 + 2AB\cos\theta}, \qquad \tan\alpha = \frac{B\sin\theta}{A + B\cos\theta}$$

DOT AND CROSS PRODUCT

$$\vec{A}\cdot\vec{B} = AB\cos\theta, \qquad |\vec{A}\times\vec{B}| = AB\sin\theta$$

COMPONENTS

$$A_x = A\cos\theta,\ \ A_y = A\sin\theta,\ \ \text{projection of } \vec{A} \text{ on } \vec{B} = \frac{\vec{A}\cdot\vec{B}}{B}$$

Calculus in physics

$$v = \frac{dx}{dt}, \qquad a = \frac{dv}{dt} = v\frac{dv}{dx}, \qquad x = \int v\,dt$$

SMALL APPROXIMATIONS

$$(1+x)^n \approx 1 + nx, \qquad \sin\theta \approx \tan\theta \approx \theta, \qquad \cos\theta \approx 1 - \frac{\theta^2}{2}\ \ (\text{small})$$

MAXIMA / MINIMA

$$\frac{dy}{dx} = 0; \qquad \frac{d^2y}{dx^2} < 0\ \text{max},\ > 0\ \text{min}$$

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CHAPTER 3

Motion in One Dimension

Kinematics in a straight line

EQUATIONS OF MOTION (CONSTANT A)

$$v = u + at, \qquad s = ut + \tfrac{1}{2}at^2, \qquad v^2 = u^2 + 2as$$

DISTANCE IN NTH SECOND

$$s_n = u + \frac{a}{2}(2n - 1)$$

AVERAGE VELOCITY

$$v_{\text{avg}} = \frac{\text{displacement}}{\text{time}}; \qquad \text{constant } a: \ \frac{u + v}{2}$$

Motion under gravity

THROWN UP WITH SPEED U

$$H = \frac{u^2}{2g}, \qquad t_{\text{up}} = \frac{u}{g}, \qquad \text{time of flight} = \frac{2u}{g}$$

DROPPED FROM HEIGHT H

$$t = \sqrt{\frac{2h}{g}}, \qquad v = \sqrt{2gh}$$

Graphs of motion

$$\text{slope of } x\text{–}t = v; \qquad \text{slope of } v\text{–}t = a; \qquad \text{area under } v\text{–}t = \text{displacement};$$

$$\text{area under } a\text{–}t = \Delta v$$

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CHAPTER 4

Motion in Two Dimensions

Projectile motion

TIME, HEIGHT, RANGE

$$T = \frac{2u\sin\theta}{g}, \qquad H = \frac{u^2\sin^2\theta}{2g}, \qquad R = \frac{u^2\sin 2\theta}{g}$$

MAXIMUM RANGE

$$R_{\max} = \frac{u^2}{g} \text{ at } \theta = 45^\circ; \qquad \theta \text{ and } 90^\circ - \theta \text{ give the same range}$$

TRAJECTORY

$$y = x\tan\theta - \frac{gx^2}{2u^2\cos^2\theta} = x\tan\theta\left(1 - \frac{x}{R}\right)$$

$$\tan\theta = \frac{4H}{R}$$

ON AN INCLINE (ANGLE A, THROWN AT Θ TO IT)

$$T = \frac{2u\sin\theta}{g\cos\alpha}, \qquad R_{\max} = \frac{u^2}{g(1+\sin\alpha)} \text{ up the incline}$$

Relative motion and river crossing

RELATIVE VELOCITY

$$\vec{v}_{AB} = \vec{v}_A - \vec{v}_B$$

SHORTEST TIME

$$t = \frac{d}{v_b} \text{ (head straight across)}, \qquad \text{drift} = \frac{v_r d}{v_b}$$

SHORTEST PATH

$$\sin\theta = \frac{v_r}{v_b} \text{ (upstream)}, \qquad t = \frac{d}{\sqrt{v_b^2 - v_r^2}}$$

RAIN–MAN

$$\vec{v}_{\text{rain, man}} = \vec{v}_{\text{rain}} - \vec{v}_{\text{man}}$$

Hold the umbrella along the relative velocity of rain.

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CHAPTER 5

Laws of Motion

Newton's laws

$$\vec{F} = \frac{d\vec{p}}{dt} = m\vec{a}, \qquad \vec{J} = \int \vec{F}\, dt = \Delta\vec{p}$$

LIFT

$$\text{apparent weight} = m(g + a) \text{ going up with } a; \qquad m(g - a) \text{ going down}$$

Friction

$$f_s \leq \mu_s N, \qquad f_k = \mu_k N$$

ANGLE OF REPOSE

$$\tan\theta = \mu_s$$

BLOCK ON AN INCLINE

$$a = g(\sin\theta - \mu_k \cos\theta) \text{ sliding down}$$

Pulleys, constraints and pseudo force

ATWOOD MACHINE

$$a = \frac{(m_1 - m_2)g}{m_1 + m_2}, \qquad T = \frac{2m_1 m_2 g}{m_1 + m_2}$$

PSEUDO FORCE

$$\vec{F}_{\text{pseudo}} = -m\vec{a}_{\text{frame}} \text{ (in an accelerating frame)}$$

STRING CONSTRAINT

$$\sum T \cdot \vec{v} = 0 \text{ (inextensible strings)}$$

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CHAPTER 6

Circular Motion

Kinematics of circular motion

$$v = \omega r, \qquad a_c = \frac{v^2}{r} = \omega^2 r, \qquad a_t = \alpha r, \qquad a = \sqrt{a_c^2 + a_t^2}$$

$$\omega = \frac{2\pi}{T} = 2\pi n, \qquad \omega = \omega_0 + \alpha t, \;\; \theta = \omega_0 t + \tfrac{1}{2}\alpha t^2$$

Dynamics and banking of roads

CENTRIPETAL FORCE

$$F = \frac{mv^2}{r}$$

FLAT ROAD

$$v_{\max} = \sqrt{\mu r g}$$

BANKED ROAD

$$\tan\theta = \frac{v^2}{rg}\ (\text{no friction}); \qquad v_{\max} = \sqrt{rg\,\frac{\mu + \tan\theta}{1 - \mu\tan\theta}}$$

CONICAL PENDULUM

$$\tan\theta = \frac{v^2}{rg}, \qquad T = 2\pi\sqrt{\frac{L\cos\theta}{g}}$$

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CHAPTER 7

Work Power Energy

Work and energy

WORK

$$W = \vec{F} \cdot \vec{s} = Fs\cos\theta, \qquad W = \int \vec{F} \cdot d\vec{r}$$

WORK–ENERGY THEOREM

$$W_{\text{net}} = \Delta K = \tfrac{1}{2}mv^2 - \tfrac{1}{2}mu^2$$

POTENTIAL ENERGY

$$F = -\frac{dU}{dx}; \qquad U = mgh; \qquad U_{\text{spring}} = \tfrac{1}{2}kx^2$$

KINETIC ENERGY AND MOMENTUM

$$K = \frac{p^2}{2m}$$

EQUILIBRIUM

$$\frac{dU}{dx} = 0; \qquad \frac{d^2U}{dx^2} > 0 \text{ stable}, \ < 0 \text{ unstable}$$

Power

$$P = \frac{dW}{dt} = \vec{F} \cdot \vec{v}, \qquad \eta = \frac{\text{output}}{\text{input}}$$

Vertical circular motion

STRING

$$v_{\text{bottom}} \geq \sqrt{5gl}, \qquad v_{\text{top}} \geq \sqrt{gl}, \qquad T_{\text{bottom}} - T_{\text{top}} = 6mg$$

ROD (RIGID)

$$v_{\text{bottom}} \geq \sqrt{4gl}$$

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CHAPTER 8

Center of Mass Momentum and Collision

Centre of mass

$$\vec{r}_{cm} = \frac{\sum m_i \vec{r}_i}{\sum m_i} = \frac{1}{M}\int \vec{r}\, dm$$

STANDARD BODIES

$$\text{semicircular ring } \frac{2R}{\pi}; \qquad \text{semicircular disc } \frac{4R}{3\pi}; \qquad \text{hemisphere (solid) } \frac{3R}{8};$$

$$\text{cone } \frac{h}{4} \text{ from base}$$

$$M\vec{a}_{cm} = \vec{F}_{\text{ext}}, \qquad \vec{p} = M\vec{v}_{cm}$$

Conservation of momentum

$$\vec{F}_{\text{ext}} = 0 \;\Rightarrow\; \sum m_i \vec{v}_i = \text{constant}$$

RECOIL

$$m_g v_g = -m_b v_b$$

VARIABLE MASS (ROCKET)

$$F = v_r \frac{dm}{dt}, \qquad v = u + v_r \ln \frac{m_0}{m}$$

Collisions

COEFFICIENT OF RESTITUTION

$$e = \frac{\text{velocity of separation}}{\text{velocity of approach}} = \frac{v_2 - v_1}{u_1 - u_2}$$

1-D COLLISION

$$v_1 = \frac{(m_1 - em_2)u_1 + (1+e)m_2 u_2}{m_1 + m_2}, \qquad v_2 = \frac{(m_2 - em_1)u_2 + (1+e)m_1 u_1}{m_1 + m_2}$$

ELASTIC, EQUAL MASSES

$$e = 1,\ m_1 = m_2 : \text{velocities exchange}$$

KE LOST IN A COLLISION

$$\Delta K = \frac{m_1 m_2}{2(m_1 + m_2)}(u_1 - u_2)^2(1 - e^2)$$

BOUNCING BALL

$$h_n = e^{2n} h$$

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CHAPTER 9

Rotational Motion

Moment of inertia

$$I = \sum mr^2 = \int r^2\,dm, \qquad I = MK^2 \ (K = \text{radius of gyration})$$

AXIS THEOREMS

$$I = I_{cm} + Md^2 \ \text{(parallel)}; \qquad I_z = I_x + I_y \ \text{(perpendicular, plane bodies)}$$

STANDARD (ABOUT THE CENTRAL AXIS)

$$\text{ring } MR^2; \quad \text{disc } \tfrac{1}{2}MR^2; \quad \text{solid sphere } \tfrac{2}{5}MR^2; \quad \text{hollow sphere } \tfrac{2}{3}MR^2$$

$$\text{rod about centre } \tfrac{1}{12}ML^2; \quad \text{about end } \tfrac{1}{3}ML^2; \quad \text{ring about diameter } \tfrac{1}{2}MR^2;$$

$$\text{disc about diameter } \tfrac{1}{4}MR^2$$

Torque and rotational dynamics

$$\vec{\tau} = \vec{r} \times \vec{F}, \qquad \tau = I\alpha, \qquad W = \int \tau\,d\theta, \qquad P = \tau\omega$$

KINETIC ENERGY

$$K = \tfrac{1}{2}I\omega^2$$

Angular momentum

$$\vec{L} = \vec{r} \times \vec{p} = I\vec{\omega}, \qquad \vec{\tau} = \frac{d\vec{L}}{dt}$$

CONSERVATION

$$\tau_{\text{ext}} = 0 \ \Rightarrow \ I_1\omega_1 = I_2\omega_2$$

Rolling motion

WITHOUT SLIPPING

$$v_{cm} = \omega R, \qquad K = \tfrac{1}{2}Mv^2\left(1 + \frac{K^2}{R^2}\right)$$

DOWN AN INCLINE

$$a = \frac{g\sin\theta}{1 + K^2/R^2}, \qquad \mu_{\min} = \frac{\tan\theta}{1 + R^2/K^2}$$

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CHAPTER 10

Gravitation

Law of gravitation and field

$$F = \frac{Gm_1m_2}{r^2}, \qquad E = \frac{GM}{r^2}$$

SHELL AND SPHERE

$$\text{shell: } E = 0 \ (r < R); \qquad \text{solid sphere: } E = \frac{GMr}{R^3} \ (r < R)$$

Acceleration due to gravity

$$g = \frac{GM}{R^2}$$

HEIGHT H

$$g_h = \frac{g}{(1 + h/R)^2} \approx g\left(1 - \frac{2h}{R}\right) \ (h \ll R)$$

DEPTH D

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

LATITUDE

$$g_\phi = g - \omega^2 R \cos^2 \phi$$

Potential, energy and escape velocity

$$V = -\frac{GM}{r}, \qquad U = -\frac{GMm}{r}$$

ESCAPE VELOCITY

$$v_e = \sqrt{\frac{2GM}{R}} = \sqrt{2gR} \approx 11.2 \text{ km/s}$$

Satellites and Kepler's laws

ORBITAL SPEED AND PERIOD

$$v_o = \sqrt{\frac{GM}{r}}, \qquad T = 2\pi\sqrt{\frac{r^3}{GM}}$$

ENERGY

$$K = \frac{GMm}{2r}, \qquad U = -\frac{GMm}{r}, \qquad E = -\frac{GMm}{2r}$$

KEPLER'S LAWS

$$T^2 \propto a^3; \qquad \frac{dA}{dt} = \frac{L}{2m} = \text{constant}$$

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CHAPTER 11

Mechanical Properties of Solids

Stress, strain and elastic moduli

$$Y = \frac{F/A}{\Delta L/L}, \qquad B = -\frac{\Delta P}{\Delta V/V}, \qquad \eta = \frac{F/A}{\theta}$$

ELONGATION

$$\Delta L = \frac{FL}{AY}; \qquad \text{own weight: } \Delta L = \frac{\rho g L^2}{2Y}$$

POISSON'S RATIO

$$\sigma = -\frac{\Delta d/d}{\Delta L/L}$$

THERMAL STRESS

$$\frac{F}{A} = Y\alpha\,\Delta T$$

COMPRESSIBILITY

$$k = \frac{1}{B}$$

Elastic potential energy

$$\frac{U}{V} = \tfrac{1}{2}\times\text{stress}\times\text{strain}, \qquad U = \tfrac{1}{2}F\,\Delta L$$

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CHAPTER 12

Mechanical Properties of Fluids

Pressure and buoyancy

$$P = P_0 + \rho g h, \qquad F_B = \rho_{\text{fluid}} V_{\text{sub}}\, g$$

FLOATING

$$\frac{V_{\text{sub}}}{V} = \frac{\rho_{\text{body}}}{\rho_{\text{fluid}}}$$

ACCELERATING CONTAINER

$$\tan\theta = \frac{a}{g} \ (\text{free surface, horizontal } a)$$

Fluid dynamics and Bernoulli's theorem

CONTINUITY

$$A_1 v_1 = A_2 v_2$$

BERNOULLI

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

TORRICELLI

$$v = \sqrt{2gh}; \qquad \text{range} = 2\sqrt{h(H-h)}$$

Viscosity

$$F = \eta A \frac{dv}{dx}, \qquad F_{\text{Stokes}} = 6\pi\eta r v$$

TERMINAL VELOCITY

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

POISEUILLE

$$Q = \frac{\pi\, \Delta P\, r^4}{8\eta l}$$

REYNOLDS NUMBER

$$R_e = \frac{\rho v D}{\eta}$$

Surface tension and capillarity

$$T = \frac{F}{L}, \qquad W = T\, \Delta A$$

EXCESS PRESSURE

$$\text{drop } \frac{2T}{r}; \qquad \text{soap bubble } \frac{4T}{r}$$

CAPILLARY RISE

$$h = \frac{2T\cos\theta}{r\rho g}$$

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CHAPTER 13

Thermal Properties of Matter

Thermal expansion

$$\Delta L = L\alpha\,\Delta T, \qquad \Delta A = A\beta\,\Delta T, \qquad \Delta V = V\gamma\,\Delta T$$

$$\alpha : \beta : \gamma = 1 : 2 : 3$$

PENDULUM CLOCK

$$\Delta t = \tfrac{1}{2}\alpha\,\Delta T \times t \text{ (time lost per } t \text{ when hotter)}$$

TEMPERATURE SCALES

$$\frac{C}{100} = \frac{F-32}{180} = \frac{K-273.15}{100}$$

Calorimetry and specific heat

$$Q = mc\,\Delta T, \qquad Q = mL, \qquad \text{heat lost} = \text{heat gained}$$

Heat transfer

CONDUCTION

$$\frac{dQ}{dt} = \frac{KA\,\Delta T}{L}, \qquad R_{\text{th}} = \frac{L}{KA}$$

SERIES AND PARALLEL

$$R = R_1 + R_2 \text{ (series)}, \qquad \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \text{ (parallel)}$$

STEFAN–BOLTZMANN

$$P = e\sigma A T^4; \qquad P_{\text{net}} = e\sigma A(T^4 - T_0^4)$$

WIEN'S LAW

$$\lambda_m T = b \approx 2.9 \times 10^{-3}\ \text{m K}$$

NEWTON'S LAW OF COOLING

$$\frac{dT}{dt} = -k(T - T_0); \qquad \frac{T_1 - T_2}{t} \approx k\left(\frac{T_1 + T_2}{2} - T_0\right)$$

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CHAPTER 14

Thermodynamics

First law and processes

FIRST LAW

$$\Delta Q = \Delta U + W, \qquad \Delta U = nC_v\,\Delta T, \qquad W = \int P\,dV$$

ISOTHERMAL

$$W = nRT\ln\frac{V_2}{V_1}, \qquad \Delta U = 0$$

ADIABATIC

$$PV^{\gamma} = \text{const}, \qquad TV^{\gamma-1} = \text{const}, \qquad W = \frac{P_1V_1 - P_2V_2}{\gamma - 1}$$

ISOBARIC / ISOCHORIC

$$W = P\,\Delta V,\ \ Q = nC_p\Delta T\ \ (P\ \text{const}); \qquad W = 0,\ \ Q = nC_v\Delta T\ \ (V\ \text{const})$$

POLYTROPIC

$$PV^{x} = \text{const}: \quad W = \frac{nR\,\Delta T}{1-x}, \qquad C = C_v + \frac{R}{1-x}$$

SLOPES ON P–V

$$\text{adiabatic slope} = \gamma \times \text{isothermal slope}$$

Heat engines, refrigerators and second law

EFFICIENCY

$$\eta = \frac{W}{Q_1} = 1 - \frac{Q_2}{Q_1}; \qquad \eta_{\text{Carnot}} = 1 - \frac{T_2}{T_1}$$

REFRIGERATOR

$$\beta = \frac{Q_2}{W} = \frac{T_2}{T_1 - T_2}\ (\text{Carnot})$$

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CHAPTER 15

Kinetic Theory of Gases

Ideal gas and kinetic theory

$$PV = nRT = Nk_BT, \qquad P = \tfrac{1}{3}\rho v_{\text{rms}}^2$$

AVERAGE KE

$$\bar{E} = \tfrac{3}{2}k_BT \text{ per molecule (translational)}$$

Molecular speeds and mean free path

$$v_{\text{rms}} = \sqrt{\frac{3RT}{M}}, \qquad v_{\text{avg}} = \sqrt{\frac{8RT}{\pi M}}, \qquad v_{\text{mp}} = \sqrt{\frac{2RT}{M}}$$

MEAN FREE PATH

$$\lambda = \frac{1}{\sqrt{2}\,\pi d^2 n} = \frac{k_BT}{\sqrt{2}\,\pi d^2 P}$$

Degrees of freedom and specific heats

EQUIPARTITION

$$\tfrac{1}{2}k_BT \text{ per degree of freedom;} \qquad U = \frac{f}{2}nRT$$

$$C_v = \frac{f}{2}R, \qquad C_p = C_v + R, \qquad \gamma = 1 + \frac{2}{f}$$

VALUES OF F

$$\text{monatomic } 3\ (\gamma = \tfrac{5}{3}); \qquad \text{diatomic } 5\ (\gamma = \tfrac{7}{5}); \qquad \text{non-linear polyatomic } 6\ (\gamma = \tfrac{4}{3})$$

MIXTURE

$$C_v = \frac{n_1C_{v1} + n_2C_{v2}}{n_1 + n_2}$$

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CHAPTER 16

Oscillations

Simple harmonic motion

$$x = A\sin(\omega t + \phi), \qquad a = -\omega^2 x, \qquad v = \omega\sqrt{A^2 - x^2}$$

$$\omega = \frac{2\pi}{T}, \qquad v_{\max} = A\omega, \qquad a_{\max} = A\omega^2$$

Energy in SHM

$$K = \tfrac{1}{2}m\omega^2(A^2 - x^2), \qquad U = \tfrac{1}{2}m\omega^2 x^2, \qquad E = \tfrac{1}{2}m\omega^2 A^2$$

Springs and pendulums

SPRING

$$T = 2\pi\sqrt{\frac{m}{k}}; \qquad \text{series } \frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2}; \qquad \text{parallel } k = k_1 + k_2$$

SIMPLE PENDULUM

$$T = 2\pi\sqrt{\frac{l}{g}}; \qquad \text{in a lift } g \to g \pm a$$

PHYSICAL PENDULUM

$$T = 2\pi\sqrt{\frac{I}{mgd}}$$

TWO-BODY SPRING

$$T = 2\pi\sqrt{\frac{\mu}{k}}, \qquad \mu = \frac{m_1 m_2}{m_1 + m_2}$$

LIQUID IN U-TUBE

$$T = 2\pi\sqrt{\frac{L}{2g}} \quad (L = \text{total liquid length})$$

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CHAPTER 17

Waves and Sound

Wave motion

$$y = A\sin(kx - \omega t), \qquad v = f\lambda = \frac{\omega}{k}, \qquad k = \frac{2\pi}{\lambda}$$

PHASE DIFFERENCE

$$\Delta\phi = \frac{2\pi}{\lambda}\,\Delta x$$

INTENSITY

$$I = 2\pi^2 f^2 A^2 \rho v; \qquad I \propto \frac{1}{r^2}\ \text{(point source)}$$

SOUND LEVEL

$$\beta = 10\log_{10}\frac{I}{I_0}\ \text{dB}$$

Waves on a string and standing waves

SPEED

$$v = \sqrt{\frac{T}{\mu}}$$

STRING FIXED AT BOTH ENDS

$$f_n = \frac{nv}{2L}, \qquad n = 1, 2, 3, \ldots$$

STANDING WAVE

$$y = 2A\sin kx\cos\omega t; \qquad \text{node to node} = \frac{\lambda}{2}$$

Sound, organ pipes and beats

SPEED OF SOUND

$$v = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\frac{\gamma RT}{M}}; \qquad v_{\text{solid}} = \sqrt{\frac{Y}{\rho}}$$

OPEN PIPE

$$f_n = \frac{nv}{2L}, \qquad n = 1, 2, 3, \ldots$$

CLOSED PIPE

$$f_n = \frac{nv}{4L}, \qquad n = 1, 3, 5, \ldots\ \text{(odd harmonics only)}$$

END CORRECTION

$$L \to L + 0.6r \text{ (closed)}, \qquad L + 1.2r \text{ (open)}$$

BEATS

$$f_{\text{beat}} = |f_1 - f_2|$$

RESONANCE TUBE

$$v = 2f(l_2 - l_1)$$

Doppler effect

$$f' = f\,\frac{v \pm v_o}{v \mp v_s}$$

Upper signs when observer and source move towards each other.

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CHAPTER 18

Electrostatics

Coulomb's law and electric field

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}, \qquad \vec{E} = \frac{\vec{F}}{q_0}, \qquad E = \frac{kq}{r^2}\ \left(k = \frac{1}{4\pi\varepsilon_0}\right)$$

LINE OF CHARGE

$$E = \frac{\lambda}{2\pi\varepsilon_0 r}\ (\text{infinite})$$

RING (ON AXIS)

$$E = \frac{kQx}{(R^2 + x^2)^{3/2}}, \qquad E_{\max} \text{ at } x = \frac{R}{\sqrt{2}}$$

SHEET AND PLATES

$$E = \frac{\sigma}{2\varepsilon_0}\ (\text{sheet}), \qquad E = \frac{\sigma}{\varepsilon_0}\ (\text{between oppositely charged plates})$$

FIELD OF A SPHERE

$$\text{conducting/shell: } 0\ (r < R),\ \frac{kQ}{r^2}\ (r \geq R); \qquad \text{solid (uniform): } \frac{kQr}{R^3}\ (r < R)$$

Gauss's law and flux

$$\phi = \oint \vec{E} \cdot d\vec{A} = \frac{q_{\text{enc}}}{\varepsilon_0}$$

Electric potential and energy

$$V = \frac{kq}{r}, \qquad \vec{E} = -\nabla V, \qquad E = -\frac{dV}{dr}$$

POTENTIAL ENERGY

$$U = \frac{kq_1 q_2}{r}, \qquad W = q\,\Delta V$$

SPHERE

$$V = \frac{kQ}{R}\ (\text{inside a conductor}); \qquad \text{solid sphere centre } \frac{3kQ}{2R}$$

Electric dipole

$$\vec{p} = q\,\vec{d}; \qquad E_{\text{axial}} = \frac{2kp}{r^3}, \qquad E_{\text{equatorial}} = \frac{kp}{r^3}$$

$$V = \frac{kp\cos\theta}{r^2}, \qquad \vec{\tau} = \vec{p} \times \vec{E}, \qquad U = -\vec{p} \cdot \vec{E}$$

Conductors

$$E_{\text{inside}} = 0; \qquad \text{charge sits on the surface;} \qquad E_{\text{surface}} = \frac{\sigma}{\varepsilon_0}$$

CONNECTED SPHERES

$$\frac{q_1}{q_2} = \frac{r_1}{r_2}, \qquad \frac{\sigma_1}{\sigma_2} = \frac{r_2}{r_1}$$

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CHAPTER 19

Capacitance

Capacitors

$$C = \frac{Q}{V}; \qquad \text{parallel plate } C = \frac{\varepsilon_0 A}{d}; \qquad \text{sphere } C = 4\pi\varepsilon_0 R$$

SPHERICAL AND CYLINDRICAL

$$C = 4\pi\varepsilon_0 \frac{ab}{b-a}, \qquad C = \frac{2\pi\varepsilon_0 L}{\ln(b/a)}$$

Combinations

$$\text{series: } \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots; \qquad \text{parallel: } C = C_1 + C_2 + \cdots$$

CHARGING (RC)

$$q = CV\left(1 - e^{-t/RC}\right), \qquad \text{discharging: } q = q_0 e^{-t/RC}, \qquad \tau = RC$$

Dielectrics

$$C = K\frac{\varepsilon_0 A}{d}; \qquad \text{slab of thickness } t: \; C = \frac{\varepsilon_0 A}{d - t + t/K}$$

CONDUCTING SLAB

$$C = \frac{\varepsilon_0 A}{d - t}$$

Energy stored

$$U = \tfrac{1}{2}CV^2 = \frac{Q^2}{2C} = \tfrac{1}{2}QV, \qquad u = \tfrac{1}{2}\varepsilon_0 E^2$$

SHARING CHARGE

$$\Delta U = \frac{C_1 C_2 (V_1 - V_2)^2}{2(C_1 + C_2)} \text{ lost}$$

FORCE BETWEEN PLATES

$$F = \frac{Q^2}{2\varepsilon_0 A}$$

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CHAPTER 20

Current Electricity

Current, drift velocity and Ohm's law

$$I = \frac{dq}{dt} = neAv_d, \qquad V = IR, \qquad R = \frac{\rho L}{A}$$

$$J = \sigma E, \qquad \rho = \frac{m}{ne^2\tau}, \qquad \mu = \frac{v_d}{E}$$

TEMPERATURE

$$R = R_0(1 + \alpha\,\Delta T)$$

STRETCHED WIRE

$$\text{length} \times n \;\Rightarrow\; R \times n^2 \text{ (same volume)}$$

Combinations and Kirchhoff's laws

$$\text{series } R = R_1 + R_2; \qquad \text{parallel } \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

KIRCHHOFF

$$\sum I = 0 \text{ (junction)}; \qquad \sum \Delta V = 0 \text{ (loop)}$$

WHEATSTONE BRIDGE BALANCED

$$\frac{P}{Q} = \frac{R}{S}$$

Cells, EMF and internal resistance

$$V = \varepsilon - Ir, \qquad I = \frac{\varepsilon}{R + r}$$

CELLS IN SERIES / PARALLEL

$$\varepsilon_{\text{eq}} = \sum \varepsilon_i,\ r_{\text{eq}} = \sum r_i; \qquad \varepsilon_{\text{eq}} = \frac{\sum \varepsilon_i/r_i}{\sum 1/r_i},\ \frac{1}{r_{\text{eq}}} = \sum \frac{1}{r_i}$$

MAXIMUM POWER

$$R = r: \quad P_{\max} = \frac{\varepsilon^2}{4r}$$

Heating effect and power

$$P = VI = I^2R = \frac{V^2}{R}, \qquad H = I^2Rt$$

Meter bridge, potentiometer and instruments

METER BRIDGE

$$\frac{R}{S} = \frac{l}{100 - l}$$

POTENTIOMETER

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{l_1}{l_2}; \qquad r = R\left(\frac{l_1}{l_2} - 1\right)$$

GALVANOMETER CONVERSIONS

$$\text{ammeter: } S = \frac{I_g G}{I - I_g}\ \text{(shunt)}; \qquad \text{voltmeter: } R = \frac{V}{I_g} - G\ \text{(series)}$$

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CHAPTER 21

Magnetic Effects of Current

Biot–Savart and Ampère's laws

BIOT–SAVART

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{l}\times\hat{r}}{r^2}$$

STRAIGHT WIRE

$$B = \frac{\mu_0 I}{4\pi d}(\sin\theta_1 + \sin\theta_2); \qquad \text{infinite: } \frac{\mu_0 I}{2\pi d}$$

CIRCULAR LOOP

$$B_{\text{centre}} = \frac{\mu_0 I}{2R}; \qquad B_{\text{axis}} = \frac{\mu_0 I R^2}{2(R^2+x^2)^{3/2}}; \qquad \text{arc } \frac{\mu_0 I\theta}{4\pi R}$$

AMPÈRE

$$\oint \vec{B}\cdot d\vec{l} = \mu_0 I_{\text{enc}}; \qquad \text{solenoid } B = \mu_0 n I; \qquad \text{toroid } B = \frac{\mu_0 N I}{2\pi r}$$

Force on charges and currents

LORENTZ FORCE

$$\vec{F} = q(\vec{E} + \vec{v}\times\vec{B})$$

CIRCULAR PATH

$$r = \frac{mv}{qB}, \qquad T = \frac{2\pi m}{qB}, \qquad \text{pitch} = v\cos\theta\, T$$

WIRE

$$\vec{F} = I\vec{l}\times\vec{B}; \qquad \text{parallel wires } \frac{F}{L} = \frac{\mu_0 I_1 I_2}{2\pi d}$$

CYCLOTRON FREQUENCY

$$f = \frac{qB}{2\pi m}$$

Torque on a loop and galvanometer

$$\vec{M} = NI\vec{A}, \qquad \vec{\tau} = \vec{M}\times\vec{B}, \qquad U = -\vec{M}\cdot\vec{B}$$

MOVING COIL GALVANOMETER

$$NIAB = k\phi \;\Rightarrow\; \text{current sensitivity } \frac{\phi}{I} = \frac{NAB}{k}$$

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CHAPTER 22

Magnetic Properties of Matter

Bar magnet and Earth's magnetism

$$B_{\text{axial}} = \frac{\mu_0}{4\pi}\frac{2M}{r^3}, \qquad B_{\text{equatorial}} = \frac{\mu_0}{4\pi}\frac{M}{r^3}$$

EARTH

$$B_H = B\cos\delta, \qquad B_V = B\sin\delta, \qquad \tan\delta = \frac{B_V}{B_H}$$

OSCILLATION MAGNETOMETER

$$T = 2\pi\sqrt{\frac{I}{MB_H}}$$

Magnetic materials

$$B = \mu_0(H + M), \qquad \chi = \frac{M}{H}, \qquad \mu_r = 1 + \chi$$

CURIE'S LAW

$$\chi \propto \frac{1}{T}\ \text{(paramagnets)}; \qquad \chi = \frac{C}{T - T_c}\ \text{(ferromagnets above } T_c\text{)}$$

CLASSIFICATION

$$\text{dia: } \chi < 0\ \text{(small)}; \qquad \text{para: } \chi > 0\ \text{(small)}; \qquad \text{ferro: } \chi \gg 1$$

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CHAPTER 23

Electromagnetic Induction

Faraday's and Lenz's laws

$$\varepsilon = -N\frac{d\phi}{dt}, \qquad \phi = \vec{B}\cdot\vec{A}$$

MOTIONAL EMF

$$\varepsilon = Blv; \qquad \text{rotating rod: } \tfrac{1}{2}B\omega l^2$$

ROTATING COIL

$$\varepsilon = NBA\omega\sin\omega t$$

CHARGE THROUGH A CIRCUIT

$$q = \frac{\Delta\phi}{R}$$

Self and mutual inductance

$$\phi = LI, \qquad \varepsilon = -L\frac{dI}{dt}; \qquad \text{solenoid } L = \mu_0 n^2 Al$$

$$\phi_2 = MI_1, \qquad \varepsilon_2 = -M\frac{dI_1}{dt}, \qquad M \le \sqrt{L_1 L_2}$$

COMBINATIONS (NO COUPLING)

$$\text{series } L = L_1 + L_2; \qquad \text{parallel } \frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2}$$

LR circuits and energy

$$I = I_0\left(1 - e^{-tR/L}\right)\ (\text{growth}), \qquad I = I_0 e^{-tR/L}\ (\text{decay}), \qquad \tau = \frac{L}{R}$$

ENERGY

$$U = \tfrac{1}{2}LI^2, \qquad u = \frac{B^2}{2\mu_0}$$

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CHAPTER 24

Alternating Current

AC circuits and impedance

RMS VALUES

$$I_{\text{rms}} = \frac{I_0}{\sqrt{2}}, \qquad V_{\text{rms}} = \frac{V_0}{\sqrt{2}}; \qquad \text{average over half cycle } \frac{2I_0}{\pi}$$

REACTANCES

$$X_L = \omega L, \qquad X_C = \frac{1}{\omega C}$$

SERIES LCR

$$Z = \sqrt{R^2 + (X_L - X_C)^2}, \qquad \tan\phi = \frac{X_L - X_C}{R}$$

Resonance, power and power factor

RESONANCE

$$\omega_0 = \frac{1}{\sqrt{LC}}, \qquad Z = R, \qquad Q = \frac{\omega_0 L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

POWER

$$P = V_{\text{rms}} I_{\text{rms}} \cos\phi, \qquad \cos\phi = \frac{R}{Z}$$

BANDWIDTH

$$\Delta\omega = \frac{R}{L}$$

Transformers and LC oscillations

TRANSFORMER

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s} \text{ (ideal)}$$

LC OSCILLATIONS

$$q = q_0 \cos\omega t, \qquad \omega = \frac{1}{\sqrt{LC}}, \qquad \frac{q_0^2}{2C} = \tfrac{1}{2} L I_0^2$$

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CHAPTER 25

Electromagnetic Waves

Displacement current and properties

DISPLACEMENT CURRENT

$$I_d = \varepsilon_0 \frac{d\phi_E}{dt}$$

SPEED

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}, \qquad \frac{E_0}{B_0} = c, \qquad v = \frac{c}{n}$$

ENERGY AND INTENSITY

$$u = \tfrac{1}{2}\varepsilon_0 E_0^2 \text{ (average)}, \qquad I = \tfrac{1}{2}\varepsilon_0 c E_0^2$$

MOMENTUM AND PRESSURE

$$p = \frac{U}{c}; \qquad P = \frac{I}{c} \text{ (absorbed)}, \ \frac{2I}{c} \text{ (reflected)}$$

Electromagnetic spectrum

$$\text{radio} > \text{microwave} > \text{infrared} > \text{visible} > \text{UV} > \text{X-ray} > \gamma \ \text{ (wavelength, longest first)}$$

$$\text{visible: } 400\text{–}700 \text{ nm}$$

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CHAPTER 26

Ray Optics

Reflection and mirrors

MIRROR FORMULA

$$\frac{1}{v}+\frac{1}{u}=\frac{1}{f}, \qquad f=\frac{R}{2}, \qquad m=-\frac{v}{u}$$

Use the sign convention: distances measured from the pole, along the incident light positive.

PLANE MIRRORS

$$\text{images of an object between mirrors at angle } \theta: \; n=\frac{360^\circ}{\theta}-1 \;\; (\text{if } 360^\circ/\theta \text{ is even})$$

ROTATING MIRROR

$$\text{mirror turns by } \theta \Rightarrow \text{reflected ray turns by } 2\theta$$

Refraction and total internal reflection

SNELL'S LAW

$$n_1 \sin i = n_2 \sin r, \qquad n=\frac{c}{v}$$

APPARENT DEPTH

$$d'=\frac{d}{n}; \qquad \text{shift}= t\left(1-\frac{1}{n}\right)$$

CRITICAL ANGLE

$$\sin C=\frac{1}{n} \;\; (\text{denser to rarer, into air})$$

SPHERICAL SURFACE

$$\frac{n_2}{v}-\frac{n_1}{u}=\frac{n_2-n_1}{R}$$

Lenses

LENS FORMULA

$$\frac{1}{v}-\frac{1}{u}=\frac{1}{f}, \qquad m=\frac{v}{u}$$

LENS MAKER'S FORMULA

$$\frac{1}{f}=(n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)$$

POWER AND COMBINATIONS

$$P=\frac{1}{f}\;(\text{in m}); \qquad P=P_1+P_2\;(\text{in contact}); \qquad \frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{d}{f_1 f_2}$$

DISPLACEMENT METHOD

$$f = \frac{D^2 - x^2}{4D}$$

Prism and dispersion

$$A = r_1 + r_2, \qquad \delta = i + e - A$$

MINIMUM DEVIATION

$$n = \frac{\sin\frac{A+\delta_m}{2}}{\sin\frac{A}{2}}$$

THIN PRISM

$$\delta = (n-1)A$$

DISPERSION

$$\theta = (n_v - n_r)A, \qquad \omega = \frac{n_v - n_r}{n_y - 1}$$

ACHROMATIC / NO DEVIATION

$$\frac{\omega_1}{f_1} + \frac{\omega_2}{f_2} = 0; \qquad (n_1 - 1)A_1 = (n_2 - 1)A_2$$

Optical instruments

SIMPLE MICROSCOPE

$$m = 1 + \frac{D}{f}\ (\text{image at } D), \qquad m = \frac{D}{f}\ (\text{at infinity})$$

COMPOUND MICROSCOPE

$$m = \frac{v_o}{u_o}\left(1 + \frac{D}{f_e}\right); \qquad \text{at infinity } m \approx \frac{L}{f_o} \cdot \frac{D}{f_e}$$

TELESCOPE

$$m = \frac{f_o}{f_e}\ (\text{normal adjustment}), \qquad L = f_o + f_e$$

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CHAPTER 27

Wave Optics

Interference (YDSE)

FRINGE WIDTH

$$\beta = \frac{\lambda D}{d}$$

PATH DIFFERENCE

$$\Delta x = \frac{yd}{D}; \qquad \text{bright: } \Delta x = n\lambda; \qquad \text{dark: } \Delta x = (2n-1)\frac{\lambda}{2}$$

INTENSITY

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\phi; \qquad \frac{I_{\max}}{I_{\min}} = \left(\frac{\sqrt{I_1}+\sqrt{I_2}}{\sqrt{I_1}-\sqrt{I_2}}\right)^2$$

THIN SLAB IN ONE PATH

$$\text{shift} = \frac{(n-1)tD}{d}$$

IN A MEDIUM

$$\beta' = \frac{\beta}{n}$$

Diffraction

SINGLE SLIT MINIMA

$$a\sin\theta = n\lambda; \qquad \text{central maximum width} = \frac{2\lambda D}{a}$$

RESOLVING POWER

$$\theta_{\min} = \frac{1.22\lambda}{D} \text{ (telescope)}$$

FRESNEL DISTANCE

$$z_F = \frac{a^2}{\lambda}$$

Polarisation

MALUS'S LAW

$$I = I_0\cos^2\theta; \qquad \text{unpolarised through a polaroid: } \frac{I_0}{2}$$

BREWSTER'S LAW

$$\tan\theta_B = n; \qquad \theta_B + r = 90^\circ$$

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CHAPTER 28

Dual Nature of Matter

Photoelectric effect

PHOTON

$$E = h\nu = \frac{hc}{\lambda}, \qquad E(\text{eV}) \approx \frac{1240}{\lambda(\text{nm})}, \qquad p = \frac{h}{\lambda}$$

EINSTEIN'S EQUATION

$$K_{\max} = h\nu - \phi = eV_0, \qquad \phi = h\nu_0$$

stopping potential depends on frequency, not intensity; current$\propto$intensity

de Broglie wavelength

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mK}}$$

ELECTRON THROUGH V VOLTS

$$\lambda = \frac{h}{\sqrt{2meV}} \approx \frac{12.27}{\sqrt{V}}\ \text{Å}$$

THERMAL PARTICLE

$$\lambda = \frac{h}{\sqrt{3mk_BT}}$$

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CHAPTER 29

Atomic Physics

Bohr's model and hydrogen spectrum

QUANTISATION

$$mvr = \frac{nh}{2\pi}$$

RADIUS, SPEED, ENERGY

$$r_n = 0.529\frac{n^2}{Z}\ \text{Å}, \qquad v_n = 2.18\times10^6\frac{Z}{n}\ \text{m/s}, \qquad E_n = -13.6\frac{Z^2}{n^2}\ \text{eV}$$

SPECTRAL LINES

$$\frac{1}{\lambda} = RZ^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

Lyman $n_1 = 1$ (UV), Balmer $n_1 = 2$ (visible), Paschen $n_1 = 3$ (IR).

NUMBER OF LINES

$$\frac{n(n-1)}{2}\ \text{(from level } n \text{ down to the ground state)}$$

$$K = -E, \qquad U = 2E$$

X-rays

CUT-OFF WAVELENGTH

$$\lambda_{\min} = \frac{hc}{eV}$$

MOSELEY'S LAW

$$\sqrt{\nu} = a(Z - b)$$

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CHAPTER 30

Nuclear Physics

Nuclear structure and binding energy

RADIUS

$$R = R_0 A^{1/3}, \qquad R_0 \approx 1.2 \text{ fm}; \qquad \text{density is the same for all nuclei}$$

MASS DEFECT

$$\Delta m = Z m_p + (A - Z) m_n - M, \qquad E_b = \Delta m\, c^2$$

$$1 \text{ u} = 931.5 \text{ MeV}/c^2$$

Radioactivity and decay laws

$$N = N_0 e^{-\lambda t}, \qquad A = \lambda N$$

HALF-LIFE AND MEAN LIFE

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}, \qquad \tau = \frac{1}{\lambda}$$

AFTER N HALF-LIVES

$$N = N_0 \left(\frac{1}{2}\right)^n$$

DECAYS

$$\alpha: \ A - 4, \ Z - 2; \qquad \beta^- : \ Z + 1; \qquad \beta^+ : \ Z - 1; \qquad \gamma : \text{no change}$$

Fission and fusion

Q-VALUE

$$Q = (m_{\text{reactants}} - m_{\text{products}})c^2$$

fission splits heavy nuclei; fusion joins light ones; both raise binding energy per nucleon

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CHAPTER 31

Semiconductors

Semiconductors and the p-n junction

$$n_e n_h = n_i^2; \qquad \text{n-type: } n_e \gg n_h; \qquad \text{p-type: } n_h \gg n_e$$

CONDUCTIVITY

$$\sigma = e(n_e \mu_e + n_h \mu_h)$$

Diode circuits and rectifiers

RIPPLE FREQUENCY

$$\text{half-wave: } f; \qquad \text{full-wave: } 2f$$

EFFICIENCY

$$\text{half-wave } 40.6\%; \qquad \text{full-wave } 81.2\%$$

ZENER

$$\text{reverse biased beyond breakdown: voltage stays at } V_z$$

Transistors

$$I_E = I_B + I_C, \qquad \alpha = \frac{I_C}{I_E}, \qquad \beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

CE AMPLIFIER

$$A_v = -\beta \frac{R_L}{R_{\text{in}}}, \qquad A_p = \beta\, A_v$$

Logic gates

$$\text{AND } Y = AB; \qquad \text{OR } Y = A + B; \qquad \text{NOT } Y = \bar{A}; \qquad \text{NAND } \overline{AB}; \qquad \text{NOR } \overline{A + B}$$

XOR

$$Y = A\bar{B} + \bar{A}B$$

DE MORGAN

$$\overline{A + B} = \bar{A}\,\bar{B}, \qquad \overline{AB} = \bar{A} + \bar{B}$$

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CHAPTER 32

Communication Systems

Modulation

MODULATION INDEX (AM)

$$\mu = \frac{A_m}{A_c}$$

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SIDEBANDS

$$f_c \pm f_m; \qquad \text{bandwidth} = 2f_m$$

ANTENNA AND RANGE

$$\text{antenna length} \approx \frac{\lambda}{4}; \qquad d = \sqrt{2Rh_T} + \sqrt{2Rh_R}$$

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CHAPTER 33

Experimental Physics

Measuring instruments

VERNIER CALLIPERS

$$\text{LC} = 1\ \text{MSD} - 1\ \text{VSD}; \qquad \text{reading} = \text{MSR} + n \times \text{LC} - \text{zero error}$$

SCREW GAUGE

$$\text{LC} = \frac{\text{pitch}}{\text{circular scale divisions}}; \qquad \text{reading} = \text{MSR} + n \times \text{LC} - \text{zero error}$$

Experiments and error analysis

PENDULUM G

$$g = \frac{4\pi^2 l}{T^2}, \qquad \frac{\Delta g}{g} = \frac{\Delta l}{l} + 2\frac{\Delta T}{T}$$

YOUNG'S MODULUS (SEARLE)

$$Y = \frac{4MgL}{\pi d^2\, \Delta l}$$

SPECIFIC RESISTANCE

$$\rho = \frac{\pi d^2 R}{4L}$$

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