

# Contents

## 1 COMPOSITION AND RESOLUTION OF VECTORS

1-1	The fundamental indefinables of mechanics . . . . .	1
1-2	Standards and units . . . . .	1
1-3	Symbols for physical quantities . . . . .	5
1-4	Force . . . . .	6
1-5	Graphical representation of forces. Vectors . . . . .	7
1-6	Vector addition. Resultant of a set of forces . . . . .	8
1-7	Resultant of parallel and antiparallel forces . . . . .	11
1-8	Components of a vector . . . . .	12
1-9	Resultant by rectangular resolution . . . . .	14
1-10	Vector difference . . . . .	16

## 2 EQUILIBRIUM OF A PARTICLE

2-1	Introduction . . . . .	20
2-2	Equilibrium. Newton's first law . . . . .	20
2-3	Discussion of Newton's first law of motion . . . . .	23
2-4	Stable, unstable, and neutral equilibrium . . . . .	24
2-5	Newton's third law of motion . . . . .	24
2-6	Equilibrium of a particle . . . . .	26
2-7	Friction . . . . .	33

## 3 EQUILIBRIUM OF A RIGID BODY

3-1	Moment of a force . . . . .	44
3-2	Vector product. Vector moment . . . . .	47
3-3	The second condition of equilibrium . . . . .	48
3-4	Resultant of parallel forces . . . . .	53
3-5	Center of gravity . . . . .	54
3-6	Couples . . . . .	57

## 4 RECTILINEAR MOTION. SPECIAL RELATIVITY

4-1	Motion . . . . .	64
4-2	Average velocity . . . . .	64
4-3	Instantaneous velocity . . . . .	65
4-4	Average and instantaneous acceleration . . . . .	68
4-5	Velocity and coordinate by integration . . . . .	71
4-6	Uniformly accelerated motion . . . . .	74
4-7	Freely falling bodies . . . . .	76

4-8	Rectilinear motion with variable acceleration . . . . .	79
4-9	Relative velocity . . . . .	81
4-10	Graphical representation of events relative to moving coordinate systems . . . . .	85
4-11	The Lorentz-Einstein transformation . . . . .	88

**5 NEWTON'S SECOND LAW. GRAVITATION**

5-1	Introduction . . . . .	99
5-2	Newton's second law. Mass . . . . .	99
5-3	Systems of units . . . . .	101
5-4	Newton's law of universal gravitation . . . . .	103
5-5	Mass and weight . . . . .	105
5-6	Applications of Newton's second law . . . . .	108

**6 MOTION IN A PLANE**

6-1	Motion in a plane . . . . .	124
6-2	Average and instantaneous velocity . . . . .	124
6-3	Average and instantaneous acceleration . . . . .	126
6-4	Components of acceleration . . . . .	127
6-5	Motion of a projectile . . . . .	129
6-6	Circular motion . . . . .	135
6-7	Centripetal force . . . . .	138
6-8	Motion in a vertical circle . . . . .	141
6-9	Motion of a satellite . . . . .	145
6-10	Effect of the earth's rotation on $g$ . . . . .	148

**7 WORK AND ENERGY**

7-1	Introduction . . . . .	156
7-2	Work . . . . .	157
7-3	Kinetic energy . . . . .	161
7-4	Gravitational potential energy . . . . .	162
7-5	Elastic potential energy . . . . .	169
7-6	Conservative and dissipative forces . . . . .	171
7-7	Internal work . . . . .	172
7-8	Internal potential energy . . . . .	173
7-9	Power . . . . .	175
7-10	Power and velocity . . . . .	176

**8 IMPULSE AND MOMENTUM**

8-1	Impulse and momentum . . . . .	182
8-2	Conservation of linear momentum . . . . .	186
8-3	Elastic and inelastic collisions . . . . .	187
8-4	Inelastic collisions . . . . .	188
8-5	Elastic collisions . . . . .	190
8-6	Recoil . . . . .	192
8-7	Principles of rocket propulsion . . . . .	194
8-8	Relativistic change of mass with velocity . . . . .	195
8-9	Mass and energy . . . . .	199
8-10	Relativistic force transformation . . . . .	202
8-11	Transverse and longitudinal mass . . . . .	204

**9 ROTATION**

9-1 Introduction . . . . . 211  
 9-2 Angular velocity . . . . . 211  
 9-3 Angular acceleration . . . . . 213  
 9-4 Rotation with variable angular acceleration . . . . . 214  
 9-5 Rotation with constant angular acceleration . . . . . 214  
 9-6 Relation between angular and linear velocity and acceleration . . . . . 216  
 9-7 Torque and angular acceleration. Moment of inertia . . . . . 217  
 9-8 Calculation of moments of inertia . . . . . 220  
 9-9 Kinetic energy, work, and power . . . . . 225  
 9-10 Angular momentum . . . . . 227  
 9-11 Rotation about a moving axis. The top and the gyroscope . . . . . 231

**10 ELASTICITY**

10-1 Stress . . . . . 244  
 10-2 Strain . . . . . 247  
 10-3 Elasticity and plasticity . . . . . 248  
 10-4 Elastic modulus . . . . . 249  
 10-5 The force constant . . . . . 253

**11 HARMONIC MOTION**

11-1 Introduction . . . . . 256  
 11-2 Elastic restoring forces . . . . . 256  
 11-3 Definitions . . . . . 257  
 11-4 Equations of simple harmonic motion . . . . . 258  
 11-5 Motion of a body suspended from a coil spring . . . . . 265  
 11-6 The simple pendulum . . . . . 267  
 11-7 Lissajous' figures . . . . . 268  
 11-8 Angular harmonic motion . . . . . 271  
 11-9 The physical pendulum . . . . . 271  
 11-10 Center of oscillation . . . . . 272

**12 HYDROSTATICS**

12-1 Introduction . . . . . 280  
 12-2 Pressure in a fluid . . . . . 281  
 12-3 The hydrostatic paradox . . . . . 283  
 12-4 Pressure gauges . . . . . 284  
 12-5 Vacuum pumps . . . . . 285  
 12-6 Archimedes' principle . . . . . 287  
 12-7 Forces against a dam . . . . . 290

**13 SURFACE TENSION**

13-1 Surface tension . . . . . 296  
 13-2 Surface tension and surface energy . . . . . 299  
 13-3 Pressure difference across a surface film . . . . . 300

13-4	Minimal surfaces . . . . .	302
13-5	Contact angle . . . . .	304
13-6	Capillarity . . . . .	306

## 14 HYDRODYNAMICS AND VISCOSITY

14-1	Introduction . . . . .	309
14-2	The equation of continuity . . . . .	311
14-3	Bernoulli's equation . . . . .	311
14-4	Applications of Bernoulli's equation . . . . .	313
14-5	Viscosity . . . . .	317
14-6	Poiseuille's law . . . . .	320
14-7	Stokes' law . . . . .	322
14-8	Dynamic lift . . . . .	323
14-9	Reynolds number . . . . .	327

## 15 TEMPERATURE-EXPANSION

15-1	Concept of temperature . . . . .	334
15-2	Thermometers . . . . .	337
15-3	The establishment of a temperature scale . . . . .	339
15-4	The celsius, rankine, and fahrenheit scales . . . . .	343
15-5	Expansion of solids and liquids . . . . .	345
15-6	Thermal stresses . . . . .	348

## 16 HEAT AND HEAT MEASUREMENTS

16-1	Heat, a form of energy . . . . .	352
16-2	Units of heat. The mechanical equivalent of heat . . . . .	353
16-3	Heat capacity . . . . .	354
16-4	The measurement of heat capacity . . . . .	355
16-5	Experimental values of heat capacities . . . . .	357
16-6	Change of phase . . . . .	360

## 17 TRANSFER OF HEAT

17-1	Conduction . . . . .	368
17-2	Heat flow through a compound wall . . . . .	371
17-3	Radial heat flow in a sphere or cylinder . . . . .	372
17-4	Convection . . . . .	372
17-5	Radiation . . . . .	375
17-6	The complete radiator or blackbody . . . . .	376
17-7	Planck's law . . . . .	380
17-8	Wien's displacement law and Stefan's law . . . . .	382
17-9	Heat transfer by radiation . . . . .	383
17-10	Newton's law of cooling . . . . .	384

**18 THERMAL PROPERTIES OF MATTER**

18-1 Equations of state . . . . . 389  
 18-2 The ideal gas . . . . . 389  
 18-3  $pVT$ -surface for an ideal gas . . . . . 394  
 18-4  $pVT$ -surface for a real substance . . . . . 395  
 18-5 Critical point and triple point . . . . . 398  
 18-6 Effect of dissolved substances on freezing and boiling points . . . . . 404  
 18-7 Humidity . . . . . 404  
 18-8 The Wilson cloud chamber and the bubble chamber . . . . . 406

**19 THE LAWS OF THERMODYNAMICS**

19-1 Work in thermodynamics . . . . . 411  
 19-2 Work in changing the volume . . . . . 412  
 19-3 Work and heat . . . . . 413  
 19-4 The first law of thermodynamics . . . . . 414  
 19-5 Adiabatic process . . . . . 416  
 19-6 Isochoric process . . . . . 416  
 19-7 Isothermal process . . . . . 416  
 19-8 Isobaric process . . . . . 417  
 19-9 Throttling process . . . . . 417  
 19-10 Differential form of the first law . . . . . 419  
 19-11 Internal energy of a gas . . . . . 419  
 19-12 Heat capacities of an ideal gas . . . . . 420  
 19-13 Adiabatic process of an ideal gas . . . . . 422  
 19-14 The conversion of heat into work . . . . . 425  
 19-15 The gasoline engine . . . . . 428  
 19-16 The diesel engine . . . . . 429  
 19-17 The steam engine . . . . . 429  
 19-18 The second law of thermodynamics . . . . . 430  
 19-19 The refrigerator . . . . . 431  
 19-20 The Carnot cycle . . . . . 433  
 19-21 The kelvin temperature scale . . . . . 435  
 19-22 Absolute zero . . . . . 437  
 19-23 Entropy . . . . . 438  
 19-24 The principle of the increase of entropy . . . . . 440

**20 MOLECULAR PROPERTIES OF MATTER**

20-1 Molecular theory of matter . . . . . 446  
 20-2 Avogadro's number . . . . . 449  
 20-3 Equation of state of an ideal gas . . . . . 451  
 20-4 Molar heat capacity of a gas . . . . . 456  
 20-5 The principle of equipartition of energy . . . . . 457  
 20-6 Distribution of molecular speeds . . . . . 459  
 20-7 Experimental measurement of molecular speeds . . . . . 461  
 20-8 Collision cross section. Mean free path . . . . . 463  
 20-9 Viscosity of a gas . . . . . 466  
 20-10 The Clausius and van der Waals equations of state . . . . . 468

20-11 Crystals . . . . .	470
20-12 Heat capacity of a crystal . . . . .	473

**21 TRAVELING WAVES**

21-1 Introduction . . . . .	477
21-2 Mathematical representation of a traveling wave . . . . .	479
21-3 Calculation of the speed of a transverse pulse . . . . .	481
21-4 Calculation of the speed of a longitudinal pulse . . . . .	483
21-5 Adiabatic character of a longitudinal wave . . . . .	485
21-6 Waves in a canal . . . . .	488

**22 VIBRATING BODIES**

22-1 Boundary conditions for a string . . . . .	494
22-2 Stationary waves in a string . . . . .	495
22-3 Vibration of a string fixed at both ends . . . . .	498
22-4 Demonstration of the harmonic series in a vibrating string . . . . .	499
22-5 Resonance . . . . .	500
22-6 Interference of longitudinal waves . . . . .	501
22-7 Stationary longitudinal waves . . . . .	502
22-8 Vibrations of organ pipes . . . . .	505
22-9 Vibrations of rods and plates . . . . .	506

**23 ACOUSTICAL PHENOMENA**

23-1 Pressure variations in a sound wave . . . . .	510
23-2 Intensity . . . . .	510
23-3 Intensity level and loudness . . . . .	511
23-4 Quality and pitch . . . . .	513
23-5 Spherical waves . . . . .	515
23-6 Radiation from a piston. Diffraction . . . . .	515
23-7 Radiating efficiency of a sound source . . . . .	519
23-8 Beats . . . . .	520
23-9 The Doppler effect . . . . .	521
23-10 Musical intervals and scales . . . . .	525

**24 COULOMB'S LAW**

24-1 Electric charges . . . . .	529
24-2 Atomic structure . . . . .	530
24-3 The leaf electroscope and the electrometer . . . . .	532
24-4 Conductors and insulators . . . . .	533
24-5 Charging by induction. . . . .	533
24-6 Coulomb's law . . . . .	535

**25 THE ELECTRIC FIELD, GAUSS'S LAW**

25-1 The electric field . . . . .	540
25-2 Calculation of electric intensity . . . . .	542

25-3	Lines of force . . . . .	548
25-4	Gauss's law . . . . .	549
25-5	Applications of Gauss's law . . . . .	553

**26 POTENTIAL**

26-1	Line integral of electric intensity . . . . .	566
26-2	Electrical potential energy . . . . .	568
26-3	Potential . . . . .	569
26-4	Calculation of potential differences . . . . .	570
26-5	Potential in terms of charge distribution . . . . .	574
26-6	Potential gradient . . . . .	575
26-7	Field of a dipole . . . . .	576
26-8	The Millikan oil drop experiment . . . . .	580
26-9	The electron volt. Relativistic variation of mass with velocity . . . . .	582
26-10	The cathode ray oscilloscope . . . . .	583
26-11	Sharing of charge by conductors . . . . .	587
26-12	The Van de Graaff generator . . . . .	588

**27 CAPACITANCE, PROPERTIES OF DIELECTRICS**

27-1	Capacitors . . . . .	594
27-2	The parallel-plate capacitor . . . . .	594
27-3	Capacitors in series and parallel. . . . .	596
27-4	Energy of a charged capacitor . . . . .	599
27-5	Effect of a dielectric . . . . .	601
27-6	Molecular theory of induced charges on a dielectric . . . . .	603
27-7	Polarization . . . . .	605
27-8	Susceptibility, permittivity, and dielectric coefficient . . . . .	605
27-9	Displacement . . . . .	608

**28 CURRENT, RESISTANCE, AND ELECTROMOTIVE FORCE**

28-1	Current . . . . .	614
28-2	Resistivity . . . . .	617
28-3	Resistance . . . . .	620
28-4	Electromotive force . . . . .	623
28-5	Terminal voltage of a source . . . . .	627
28-6	Current-voltage diagrams . . . . .	634
28-7	Power and work in electrical circuits . . . . .	635
28-8	Thermoelectricity . . . . .	640
28-9	Applications of the fundamental thermocouple equation . . . . .	642

**29 DIRECT-CURRENT CIRCUITS AND INSTRUMENTS**

29-1	Resistors in series and in parallel . . . . .	649
29-2	Kirchhoff's rules . . . . .	652
29-3	Ammeters and voltmeters . . . . .	654
29-4	The Wheatstone bridge . . . . .	657
29-5	The ohmmeter . . . . .	658

29-6	The potentiometer . . . . .	659
29-7	The <i>R-C</i> series circuit. . . . .	659
29-8	The sweep circuit . . . . .	662
29-9	Displacement current . . . . .	663

**30 THE MAGNETIC FIELD**

30-1	Magnetism . . . . .	671
30-2	Charges, currents, and relativity. . . . .	672
30-3	Experimental study of magnetic fields . . . . .	676
30-4	Lines of induction. Magnetic flux . . . . .	678
30-5	Orbits of charged particles in magnetic fields . . . . .	679
30-6	Thomson's measurement of <i>e/m</i> . . . . .	681
30-7	Positive rays . . . . .	683
30-8	Isotopes . . . . .	685
30-9	Mass spectroscopy . . . . .	686
30-10	Atomic weights. The atomic mass unit . . . . .	687
30-11	The cyclotron . . . . .	688

**31 MAGNETIC FORCES ON CURRENT-CARRYING CONDUCTORS**

31-1	Force on a current-carrying conductor . . . . .	694
31-2	The Hall effect. . . . .	695
31-3	Force and torque on a complete circuit. Magnetic moment . . . . .	696
31-4	The spinning electron . . . . .	698
31-5	The galvanometer . . . . .	699
31-6	The pivoted-coil galvanometer . . . . .	701
31-7	The ballistic galvanometer . . . . .	702
31-8	The direct-current motor . . . . .	702
31-9	The electromagnetic pump . . . . .	704

**32 MAGNETIC FIELD OF A CURRENT**

32-1	Magnetic field of a current-carrying circuit. The Biot law . . . . .	708
32-2	Magnetic field of a long straight conductor . . . . .	709
32-3	Force between parallel conductors. The ampere and the coulomb . . . . .	711
32-4	Magnetic field of a circular turn . . . . .	713
32-5	Ampere's law . . . . .	715
32-6	Applications of Ampere's law . . . . .	716
32-7	Magnetic field of a displacement current . . . . .	719

**33 INDUCED ELECTROMOTIVE FORCE**

33-1	Motional electromotive force . . . . .	725
33-2	Induced electric fields . . . . .	726
33-3	Induced electromotive force. The Faraday law . . . . .	729
33-4	Lenz's law . . . . .	731
33-5	The search coil . . . . .	735
33-6	Galvanometer damping . . . . .	736



33-7 Eddy currents . . . . .	737
33-8 The betatron . . . . .	739
33-9 Mutual inductance . . . . .	741
33-10 Self-inductance . . . . .	743
33-11 Energy associated with an inductor . . . . .	744
33-12 The <i>R-L</i> circuit . . . . .	745
33-13 The <i>L-C</i> circuit . . . . .	746
33-14 The <i>R-L-C</i> circuit . . . . .	748

**34 MAGNETIC PROPERTIES OF MATTER**

34-1 Equivalent surface currents . . . . .	757
34-2 Molecular theory of dia- and paramagnetism . . . . .	759
34-3 Magnetization. Magnetic intensity . . . . .	761
34-4 Magnetic susceptibility, permeability, and magnetic coefficient . . . . .	762
34-5 Ferromagnetism . . . . .	765
34-6 Magnetization of iron. Magnetic domains . . . . .	766
34-7 Hysteresis . . . . .	769
34-8 Magnetic poles . . . . .	772
34-9 Demagnetizing fields . . . . .	775
34-10 The magnetic field of the earth . . . . .	777
34-11 The magnetic circuit . . . . .	778

**35 ALTERNATING CURRENTS**

35-1 Introduction . . . . .	783
35-2 Circuits containing resistance, inductance, or capacitance . . . . .	783
35-3 The <i>R-L-C</i> series circuit . . . . .	788
35-4 Average and root-mean-square values. AC instruments . . . . .	790
35-5 Power in AC circuits . . . . .	793
35-6 Series resonance . . . . .	796
35-7 Circuits in parallel . . . . .	797
35-8 The transformer . . . . .	798

**36 ELECTROMAGNETIC WAVES**

36-1 Introduction . . . . .	804
36-2 Propagation of an electromagnetic wave . . . . .	804
36-3 Electromagnetic waves in matter . . . . .	811
36-4 The Poynting vector . . . . .	811
36-5 Sinusoidal waves . . . . .	815
36-6 Stationary waves . . . . .	817
36-7 Radiation of electromagnetic waves from an antenna . . . . .	819

**37 THE NATURE AND PROPAGATION OF LIGHT**

37-1 The nature of light . . . . .	823
37-2 Sources of light . . . . .	824
37-3 Waves, wavefronts, and rays . . . . .	827
37-4 The speed of light . . . . .	830

37-5	The laws of reflection and refraction . . . . .	832
37-6	Index of refraction . . . . .	834

### 38 REFLECTION AND REFRACTION AT PLANE SURFACES

38-1	Huygens' principle . . . . .	838
38-2	Derivation of the law of reflection from Huygens' principle . . . . .	840
38-3	Derivation of Snell's law from Huygens' principle . . . . .	841
38-4	Total internal reflection . . . . .	843
38-5	Refraction by a prism . . . . .	845
38-6	Dispersion . . . . .	847
38-7	The rainbow . . . . .	848

### 39 IMAGES FORMED BY A SINGLE REFLECTION OR REFRACTION

39-1	Introduction . . . . .	852
39-2	Reflection at a plane mirror . . . . .	852
39-3	Reflection at a spherical mirror . . . . .	855
39-4	Sign conventions . . . . .	857
39-5	Focal point and focal length . . . . .	860
39-6	Graphical methods . . . . .	862
39-7	Refraction at a plane surface . . . . .	864
39-8	Refraction at a spherical surface . . . . .	866
39-9	Summary . . . . .	869

### 40 LENSES AND OPTICAL INSTRUMENTS

40-1	Images as objects . . . . .	872
40-2	The thin lens . . . . .	873
40-3	Diverging lenses . . . . .	877
40-4	Graphical methods . . . . .	879
40-5	Images as objects for lenses . . . . .	880
40-6	Lens aberrations . . . . .	881
40-7	The eye . . . . .	881
40-8	The magnifier . . . . .	884
40-9	The camera . . . . .	885
40-10	The projection lantern . . . . .	886
40-11	The microscope . . . . .	887
40-12	The telescope . . . . .	888

### 41 INTERFERENCE AND DIFFRACTION

41-1	Principles of interference. Coherent sources . . . . .	895
41-2	Young's double slit and Pohl's mica sheet . . . . .	898
41-3	Intensity distribution in interference fringes . . . . .	902
41-4	Phase change in reflection. Lloyd's mirror . . . . .	903
41-5	The Michelson interferometer . . . . .	905
41-6	The Michelson-Morley experiment . . . . .	907
41-7	Interference in thin films. Newton's rings . . . . .	911
41-8	Thin coatings on glass . . . . .	913

41-9	Fresnel diffraction . . . . .	917
41-10	Fraunhofer diffraction by a single slit . . . . .	920
41-11	The plane diffraction grating . . . . .	923
41-12	Diffraction of x-rays by a crystal . . . . .	927
41-13	The resolving power of optical instruments . . . . .	928

**42 POLARIZATION**

42-1	Polarization . . . . .	934
42-2	Polarization by reflection. . . . .	935
42-3	Double refraction . . . . .	937
42-4	Polarization by double refraction . . . . .	939
42-5	Percentage polarization. Malus' law . . . . .	940
42-6	The scattering of light . . . . .	942
42-7	Circular and elliptic polarization . . . . .	944
42-8	Production of colors by polarized light. . . . .	946
42-9	Optical stress analysis . . . . .	947
42-10	Study of crystals by convergent polarized light . . . . .	949
42-11	Optical activity . . . . .	949

**43 ATOMS, ELECTRONS, AND PHOTONS**

43-1	Conduction in gases . . . . .	952
43-2	Thermionic emission . . . . .	953
43-3	The triode . . . . .	956
43-4	The photoelectric effect . . . . .	957
43-5	Line spectra . . . . .	959
43-6	The Bohr atom . . . . .	961
43-7	Deuterium . . . . .	966
43-8	Wave mechanics . . . . .	967
43-9	The electron microscope . . . . .	968
43-10	Absorption spectra . . . . .	970
43-11	The laser . . . . .	973
43-12	Band spectra . . . . .	974
43-13	The x-ray tube . . . . .	975
43-14	X-ray spectra . . . . .	976

**44 RADIOACTIVITY AND NUCLEAR PHYSICS**

44-1	Natural radioactivity . . . . .	982
44-2	Alpha particles . . . . .	983
44-3	Rutherford's scattering experiment . . . . .	984
44-4	Beta particles . . . . .	986
44-5	Gamma rays . . . . .	987
44-6	Radioactive transformations . . . . .	988
44-7	Artificial nuclear disintegration . . . . .	991
44-8	Cosmic rays. The positron . . . . .	992
44-9	Neutrons and mesons. . . . .	994
44-10	Nuclear stability . . . . .	997
44-11	Nuclear fission. . . . .	999
44-12	Thermonuclear reactions . . . . .	1000

**xvi Contents**

Answers to Odd-Numbered Problems . . . . .	1002
Natural Trigonometric Functions . . . . .	1013
Common Logarithms . . . . .	1014
Periodic Table of the Elements . . . . .	1016
Fundamental Constants . . . . .	1017
Conversion Factors . . . . .	1018
Index . . . . .	1019