

PREFACE

1 INTRODUCTION

1.1 The Problem of Description 1 1.2 The Realm of the Natural Sciences 2 1.3 The Divisions of Science 3 1.4 Observation and Experiment 3 1.5 The Role of Physical Theory 4 1.6 The Interplay of Experiment and Theory 5 1.7 The Validity of Physical Theory 5 References 6

2 LENGTH AND TIME

2.1 Change 8 2.2 Comparison 8 2.3 Rigid Rods 9 2.4 The Comparison of Lengths 10 2.5 Standards of Length 12 2.6 The Power of Ten Notation 13 2.7 Units and Their Relations 15 Exercises 16 2.8 The Process of Measurement 16 2.9 The Use of Significant Figures in Calculations 19 2.10 Positive and Negative 19 Exercises 21 2.11 Recapitulation 22 2.12 Before and After 22 2.13 The Ordering of Events 23 2.14 Duration 23 2.15 Periodic Processes 24 2.16 The Test for Good Clocks 24 Exercises 26 2.17 The Earth as a Clock 27 2.18 Rotational Motions-Angle 28 Exercises 31 2.19 Oscilla-Exercise 28 2.20 Practical Clocks 35 2.21 The Stroboscope 37 tions 31 Exercise 35 Exercise 37 2.22 Summary 38 Problems 38 References 39

3 LINEAR MOTIONS

3.1 Motion 40 **3.2** Change of Position and Speed 41 **3.3** Speed and Velocity; Distance and Displacement 42 Exercises 43 **3.4** Variable and Instantaneous Velocities 44 **3.5** Instantaneous Speed in SHM 48 **3.6** Instantaneous Speed as a Slope 50 Exercises 52 **3.7** Motions at Constant Velocity—The Speed of Photons 53 Exercises 56 **3.8** Acceleration 57 Exercises 59 **3.9** Motions of Constant Acceleration—Free Fall 60 Exercises 62 **3.10** An Alternative Treatment of Falling Body Data 63 **3.11** Three Graphs for the Same Motion 65 Exercises 67 **3.12** Algebraic Determination of Instantaneous Speed 67 Exercises 68 **3.13** Algebraic Determination of Instantaneous Acceleration 69 **3.14** Constant Acceleration and Area Under the Curve 69 **3.15** Summing Speed Increments Algebraically 71 **3.16** Areas Under a Speed vs. Time Curve 73 **3.17** Analytic Determination of Distance Traveled from the Speed vs. Time Curve 76 Exercises 78 **3.18** The General Equations of Uniformly Accelerated Motion 78 **3.19** An Illustrative Example 79 Exercises 80 **3.20** Summary 80 Problems 81 References 82

4 MASS, MOMENTUM, FORCE, AND ENERGY

4.1 The Inertia of Matter 83
4.2 Collisions of Equal Masses 83 Exercise 88
4.3 The Comparison of Masses by Collision 88
4.4 Standards of Mass 91
Exercises 92
4.5 The Conservation of Momentum 92
4.6 Conservation Laws 94
4.7 The Conservation of Mass 94 Exercises 95
4.8 The Notion of Force 96
4.9 Force and the Conservation of Momentum 96
4.10 Units of Force 96
4.9 Force and the Conservation of Momentum 96
4.10 Units of Force 96
4.9 Force and the Conservation of Momentum 96
4.10 Units of Force 98
Exercises 98
4.11 Impulse and Work 99
4.12 Units and Dimensions of Impulse, Work, and Energy 100 Exercises 101
4.13 Forces During Collisions 101
4.14 Kinetic Energy Exchange in Collisions 103
4.15 Weight 105 Exercises 106
4.16 The Equal Arm Balance 107
4.17 Inertial Mass and Gravitational Mass 108
4.18 Gravitational Potential Energy 108
4.19 Summary 110 Problems 111
References 112

40

83

v

1

viii CONTENTS

5 MOTIONS IN SPACE

5.1 Coordinates 113
 5.2 Coordinate Systems 114 Exercises 116
 5.3 Displacement 117
 5.4 Newtonian Relativity 118
 5.5 Vectors 112 Exercises 124
 5.6 Velocity as a Vector 124 Exercises 126
 5.7 Some Problems in Aerial Navigation 126 Exercises 131
 5.8 Vector Components 131
 5.9 Illustrative Examples 134 Exercises 137
 5.10 Summary 137 Problems 137 References 139

6 MOMENTUM, FORCE, AND ENERGY IN SPACE

6.1 A More General Interpretation of the Conservation of Momentum 140 Exercises 143
6.2 Force and Acceleration 143 Exercises 146
6.3 Resolution and Composition of Forces 146
6.4 The Condition for Translational Equilibrium 148
6.5 Some Illustrative Examples 150 Exercises 153
6.6 Work and Energy 153 Exercises 155
6.7 Products of Vectors 155 Exercises 156
6.8 Power 157 Exercises 158
6.9 Energy 158
6.10 The Conservation of Mechanical Energy 158
6.11 Summary 162 Problems 163 References 165

7 ROTATION

7.1 Angular Displacement of a Rigid Body 166 Exercise 169
7.2 Angular Velocity 169
7.3 Rotation of a Rigid Body About a Fixed Axis 172 Exercises 174
7.4 Axial Vectors 174 Exercises 175
7.5 Motion in a Circle 176 Exercise 178
7.6 Rotational Kinetic Energy and Moment of Inertia 178 Exercises 181
7.7 Centripetal Acceleration 181 Exercises 183
7.8 Centrifugal Accelerations and Forces 183 Exercises 184
7.9 Torque and Moment of a Force 184
7.10 Angular Momentum 187 Exercises 188
7.11 The Law of Conservation of Angular Momentum 188 Exercises 191
7.12 The Analogy between Linear and Rotational Dynamics 191
7.13 The Motion of the Planets 192 Exercises 195
7.14 Rotational Equilibrium 196
7.15 Center of Mass 197
7.16 General Conditions of Equilibrium 200 Exercises 202
7.17 Angular Velocity and Angular Momentum 202 Exercises 206
7.18 Summary 206 Problems 207 References 210

8 SPECIAL RELATIVITY

8.1 The Scarch for an Absolute Reference Frame 211
8.2 The Michelson-Morley Experiment 211
8.3 Einstein's Assumptions 213
8.4 Time Dilation 214
8.5 The Lorentz Contraction 217
8.6 The Lorentz Transformation 219
8.7 Simultaneity 223 Exercises 224
8.8 The Einstein Velocity Transformation 224
Exercises 226
8.9 The Dependence of Mass on Relative Motion 226 Exercises 229
8.10 Forces in Special Relativity 229
8.11 Kinetic Energy 231
8.12 The Mass-Energy Relation 233 Exercises 234
8.13 Conservation in Special Relativity 234
8.14 Evidence for the Validity of Special Relativity 236
8.15 A Note on General Relativity 236 Problems 236 References 238

9 SOME PROPERTIES OF MATTER

9.1 Introduction 239
9.2 Density and Specific Gravity 239 Exercises 241
9.3 The Elasticity of Solids 241 Exercises 245
9.4 Work and Elastic Potential Energy 246 Exercises 249
9.5 The Elasticity of Liquids 249
9.6 Hydrostatic Pressure 252 Exercises 253
9.7 A Preliminary Study of the Atmosphere 254 Exercises 255
9.8 The Principle of Archimedes 255
9.9 Application to Floating Bodies 257 Exercises 258
9.10 Summary 259 Problems 259 References 262

10 WAVE MOTION

10.1 The Transmission of Energy 263
10.2 Waves in a Train 264 Exercises 268
10.3 Calculation of the Wave Speed in a Train 268
10.4 The Speed of a Longitudinal Wave in a Rod 270 Exercises 271
10.5 Periodic Waves 272
10.6 Waves in Space 274
10.7 Energy in Waves 275
10.8 Sound Sources and Sound Waves 275
10.9 Relations between Sound Waves and Hearing 277 Exercises 278
10.10 The Principle of Superposition 278
10.11 The Reflection of Waves 280 Exercises 286
10.12 Transverse Waves 287 Exercises 291
10.13 Standing Waves 291
10.14 Vibrating Strings 292
10.15 Organ Pipes 293
10.16 Summary 295 Problems 295 References 297

239

263

113

140

166

11 THERMAL PHENOMENA

11.1 The Notion of Temperature 299 11.2 The Celsius (Centigrade) Temperature Scale 300 11.3 Coefficients of Thermal Expansion 301 11.4 Differential Expansion and the Expansion of Liquids 304 11.5 Thermometers 305 Exercises 307 11.6 Friction 307 11.7 Heat as a Form of Energy 309 11.8 The Experiments of Joule 310 11.9 The Specific Heat of Water 311 11.10 Heat Engines 312 11.11 The First Law of Thermodynamics 313 Exercises 313 11.12 Specific Heats 314 Exercises 316 11.13 Fusion 317 11.14 Variation of the Melting Point 319 Exercises 320 11.15 Vaporization and Vapor Pressure 320 11.16 The Latent Heat of Vaporization 322 11.17 Boiling 324 11.18 Sublimation 325 Exercises 326 11.19 Heat Transfer 326 Exercises 328 11.20 The Dewar Flask 328 Exercises 329 11.21 Summary 329 Problems 329 References 330

12 RADIATION

12.1 Light and Heat Radiation 331 12.2 The Rectilinear Propagation of Light 12.3 The Laws of Reflection 333 Exercises 334 12.4 The Law of Refrac-331 tion 334 **12.5** The Speed of Light in Material Bodies 336 **12.6** Total Reflection 336 Exercises 337 12.7 The Intensity of Light 338 12.8 The Inverse Square Law 339 12.9 Fermat's Principle 340 12.10 Theories of Light 342 12.11 The Propagation of Photons 343 Exercises 344 12.12 The Reflection and Refraction of Photons 344 12.13 Recapitulation of the Particle Theory 346 12.14 Interfercnce of Waves 347 **12.15** The Diffraction Grating 352 **12.16** Determination of the Wavelength of Light 354 Exercises 356 12.17 Huygens' Principle 356 Exercises 358 12.18 Wave Theory of Reflection and Refraction 358 12.19 Dis-12.20 Diffraction and Rectilinear Propagation 362 12.21 The persion 361 12.22 The Doppler Effect 364 Wave-Particle Duality 363 Exercises 364 Exercises 367 12.23 Summary 367 Problems 368 References 370

13 OPTICAL INSTRUMENTS

13.1 The Plane Mirror 372 Exercises 374
13.2 Lenses 375
13.3 Thin Lenses with Spherical Surfaces 378 Exercises 383
13.4 Images of Point Objects 383
13.5 Formation of Extended Images 384
13.6 Magnification 386 Exercises 388
13.7 Virtual Objects 389 Exercises 390
13.8 Defects of Lenses 390 Exercises 390
13.9 The Camera 392
13.10 The Eye as a Camera 393
13.11 Oculars 394 Exercises 395
13.12 The Microscope 396
13.13 The Telescope 397
Exercises 399
13.14 Spherical Mirrors 400 Exercises 400
13.15 The Spectroscope 400
13.16 Summary 403 Problems 403 References 404

14 THE GRAVITATIONAL FIELD OF FORCE

14.1 Action at a Distance 405
14.2 Kepler's Laws and Gravitation 405
14.3 Some Properties of Ellipses 408 Problems 412
14.4 Conservation of Energy in Planetary Motion 412
14.5 Newton's Law of Universal Gravitation 416 Exercises 418
14.6 The Gravitational Constant 418 Exercises 420
14.7 Field Strength 421
14.8 Lines of Force and Gravitational Displacement 423
14.9 Lines and Tubes of Displacement 424
14.10 Gravitational Flux 427
14.11 Gauss' Law 428 Exercises 432
14.12 The General Relativity Theory of Gravitation 432
14.13 Summary 437 Problems 437 References 440

15 STATIC ELECTRIC AND MAGNETIC FIELDS

15.1 Introduction 441
15.2 Some Electrical Phenomena 441
15.3 Conductors and Insulators 442
15.4 Electric Induction and Electrical Machines 444
15.5 Quantity of Electricity and Coulomb's Law 447
15.6 The Dielectric Constant 448 Exercises 449
15.7 Electric Field Strength and Displacement 449
15.8 Gauss' Law for Electrostatics 451 Exercises 452
15.9 The Behavior of an Electric Dipole 452 Exercises 453
15.10 The Use of Dipoles for Investigating Fields 453 Exercise 454
15.11 Magnets 454
15.12 The Magnetic Dipole 456
15.13 The Field About a Magnet 457
15.14 The Earth as a Magnet 458
15.15 Magnetization 459
15.16 Summary 460 Problems 461 References 465

372

405

299

331

¥

16 ELECTRIC CURRENTS AND POTENTIALS

.16.1 The Electric Current 466 16.2 Conductors in Series and Parallel 468 *Exercises* 470 **16.3** Magnetic Effects of Currents 471 **16.4** The Magnetic Dipole Moment of a Circular Coil 473 16.5 Magnetic Flux Density and Magnetic Flux 475 16.6 The Field Near a Long, Straight Wire 476 16.7 Definition of the Ampere 478 **16.8** Some Remarks About μ_0 , ϵ_0 , 4π , and Systems of Units 480 Exercises 482 16.9 Ampère's Law 483 16.10 The Magnetic Fields of Solenoids and Other Coils 486 Exercises 489 16.11 The Effect of the Medium 490 16.12 Magnetic Field Strength 490 16.13 The Galvanometer 491 16.14 Heating Effects of Currents and the Definition of Potential 492 16.15 Gravitational 16.16 Ohm's Law 495 16.17 Combinations of Potential 495 Exercises 495 Resistances 497 Exercises 500 16.18 Resistivity and Conductivity 501 Exercises 502 16.19 The Ammeter 503 16.20 The Voltmeter 504 Exercises 505 16.21 Electrostatic Potential 506 Exercises 509 16.22 The Plane Parallel Plate Capacitor—Capacitance 509 Exercises 511 16.23 Summary 512 Problems 512 References 515

17 ELECTROMAGNETIC INDUCTION

17.1 Force on a Current-carrying Wire 516 Exercises 518 17.2 Force on a Moving Charge 518 Exercises 520 17.3 Thermionic Emission 520 17.4 The Electronic Mass 521 Exercises 523 17.5 Electromagnetic Induction 523 17.6 Calculation of the Induced Electromotive Force 524 17.7 The General Law of Induction 527 Exercises 528 17.8 Induction in a Rotating Coil 529 17.9 Power from Alternators 531 Exercises 532 17.10 Mutual Inductance 534 17.11 Self-Inductance 535 Exercises 537 17.12 Inductances Carrying Alternating Currents 537 17.13 The Transformer 539 Exercises 540 17.14 Summary 541 Problems 541 References 545

18 MOLECULES AND ATOMS

18.1 Historical Background to Atomic Theories 546
18.2 Homogeneity and Heterogeneity 546
18.3 Fractionation Methods 547
18.4 Pure Substances 548
18.5 Chemical Reactions and the Law of Definite Proportions 549
18.6 Elements and Compounds 549
18.7 The Law of Multiple Proportions 549
18.8 The Atomic Hypothesis 550
18.9 Some Chemical Equations 553 Exercises 553
18.10 An Electrochemical Reaction 554
18.11 The Ionic Theory of Solutions 557
18.12 The Elementary Charge of Electricity 558
18.13 The Masses of Atoms 560
18.14 Avogadro's Number 561
18.15 The Second Law of Electrolysis 562
Exercises 563
18.16 A Simple Primary Cell 563
18.17 Internal Resistance of Cells 565
Exercises 567
18.18 Cells in Series and in Parallel 567
Exercises 569
18.19 Summary 570
Problems 570

19 ATOMIC AND NUCLEAR STRUCTURE

19.1 Introduction 573 19.2 Conduction of Electricity Through Gases 573 19.3 The Mass Spectrograph 575 19.4 Isotopes 577 19.5 The Discovery of Radioactivity 581 19.6 The Scattering of Alpha-Particles and the Rutherford Atom Model 583 **19.7** Natural Radioactivity 586 **19.8** Transmutation 588 19.9 The Discovery of the Neutron 588 Exercises 590 19.10 The Energy of Transmutation 591 19.11 Energy Units 592 19.12 Electrostatic Accelerators 593 19.13 The Cyclotron 595 19.14 The Problem of Synchronization 597 19.15 The Betatron 598 Exercises 601 19.16 Linear Accelerators 601 Exercises 603 19.17 Cosmic Radiation 603 19.18 Types of Transmutations 604 19.19 Artificial Radioactivity 606 19.20 Elementary Particles 607 Exercises 611 19.21 Structure 612 19.22 Nuclear Energy 618 19.23 The Transuranic Nuclear Elements 612 19.24 Nuclear Fission and Atomic Energy 622 19.25 The Controlled Release of Nuclear Energy 623 19.26 Nuclear Fusion 626 19.27 Applications of Artificial Radioactivity 627 Exercises 627 19.28 Summary 628 Problems 628 References 632

546

573

466

- THE BEHAVIOR AND THEORY OF GASES
 20.1 Boyle's Law 633 20.2 The Thermal Expansion of Gases 635 20.3 The Kelvin Temperature Scale 637 20.4 The Ideal Gas Law 637 Exercises 639 20.5 The Gas Thermometer 639 20.6 The Molar Heats of Gases 640 20.7 The Elastic Moduli of Gases 644 Exercises 646 20.8 The Kinetic Theory of Gases 646 20.9 The Theory of Molar Heats of Gases 651 20.10 Diffusion 652 Exercises 654 20.11 Measurement of Molecular Speeds 654 20.12 Brownian Motion 655 20.13 Real Gases 656 20.14 The Second Law of Thermodynamics 657 20.15 Summary 660 Problems 660 References 662
- THE BEHAVIOR AND THEORY OF LIQUIDS AND SOLIDS 664
 21.1 Gases, Solids, and Liquids 664
 21.2 Forces Between Atoms 665
 21.3 The Packing of Atoms 669
 21.4 The Size of Atoms 672
 21.5 X-ray Diffraction from Crystals 673
 Exercises 675
 21.6 Elastic Properties of Solids 675
 21.7 Thermal Effects in Solids 676
 21.8 Electrical Conduction 678
 21.9 Superconductors 680
 21.10 Ferromagnetism 681
 21.11 Surface Energy 683
 21.12 The Structure of Liquids 684
 Exercises 686
 21.13 Surface Tension 687
 21.14 Interfacial Tensions and the Wetting of Surfaces 688
 21.15 Capillary Attraction 690
 Exercises 691
 21.16 Vaporization and Sublimation 691
 Exercises 692
 21.17 Thermionic Emission 692
 Exercises 693
 21.18 Summary 693
 Problems 694
 References 695

22 OSCILLATIONS

22.1 Simple Harmonic Motion 697 Exercises 698
22.2 The Oscillation of a Mass on a Spring 699 Exercises 701
22.3 Rotational Oscillations 701
22.4 The Simple Pendulum 702 Exercises 703
22.5 The Effect of Friction on a Harmonic Oscillator 703
22.6 Forced Motion of a Damped Oscillator 706 Exercises 709
22.7 The Elements of an Oscillator 710 Exercises 711
22.8 The Analogy Between Electrical and Mechanical Quantities 711 Exercises 716
22.9 The Parallel Resonant Circuit 717
22.10 The Electronic Diode Vacuum Tube 719
22.13 The Transistor 725
22.14 Amplifiers 726
22.15 The Electronic Oscillator 728
22.16 Summary 729 Problems 730 References 732

23 ELECTROMAGNETIC WAVES

23.1 The Conditions Necessary for Wave Propagation 733 **23.2** The Localization of Electric Energy 733 **23.3** The Localization of Magnetic Energy 735 **23.4** The Interaction of Electric and Magnetic Fields 736 *Exercises* 738 **23.5** Maxwell's Equations 739 **23.6** The Mechanism of Energy Exchange 742 **23.7** The Speed of Propagation of Electromagnetic Waves 744 *Exercises* 745 **23.8** The Transverse Nature of Electromagnetic Waves 746 **23.9** The Radiation of Periodic Waves 747 **23.10** The Detection of Electromagnetic Radiation 749 **23.11** Reflection and Interference 751 *Exercises* 754 **23.12** Polarization 754 **23.13** Polarization of Light Waves 756 **23.14** Additional Evidence for the Identity of Light and Electromagnetic Waves 750 **23.15** The Modulation of Radio Waves 758 **23.16** Radio Receivers—Demodulation 760 **23.17** Frequency Modulation 761 **23.18** Summary 762 *Problems* 763 *References* 766

24 WAVES AND PARTICLES

24.1 Theories of Light 767
24.2 The Quantum Theory and the Photoelectric Effect 767
24.3 The Compton Effect 771
24.4 The de Broglie Hypothesis 774
24.5 The Davisson-Germer Experiment 776 Exercises 777
24.6 The Heisenberg Uncertainty Principle 777 Exercises 779
24.7 Probability in Quantum Mechanics 780
24.8 The Combination of Waves of Different Wavelengths 783
24.9 Wave Velocity and Group Velocity 784 Exercises 786
24.10 A Note on Complex Numbers and Wave Amplitudes 787
24.13 Reflection of Electrons from a Potential Step 794
24.14 Summary 797 Problems 798 References 801

733

767

633

xii CONTENTS

25 ATOMIC THEORY

25.1 Review of Evidence Regarding Atoms 802 25.2 The Evidence of Spectra 802 Exercises 804 25.3 The Energy States of the Hydrogen Atom 804 25.4 The Determination of Planck's Constant from Spectral Excitation Data 806 25.5 The Bohr-Sommerfeld Atom Model 807 Exercises 810 25.6 Elliptical Orbits 811 25.7 Ionization and Ionization Potential 813 Exercises 814 25.8 The Quantum Mechanical Atom 815 25.9 Orbital Magnetic Moment 817 25.10 Quantization of Angular Momentum and Its Components 819 25.11 Electron Spin 821 25.12 The Structure and Properties of Complex Atoms 822 25.13 X-ray Spectra 824 25.14 Moseley's Law and Atomic Numbers 826 Exercises 827 25.15 Nuclear Energy Levels—Gamma-Ray Emission 827 25.16 Isomers 828 25.17 The Hydrogen Molecule and Electron-Pair Binding 828 25.18 Exchange Forces 830 25.19 Summary 832 Problems 832 References 834

APPENDICES

A Greek Alphabet 835 B Uncertainties and Significant Figures 835 Exercises 839 C Mathematical Symbols 839 D Units and Dimensions 844 Exercises 849 E Some Properties of Right Triangles 850 F Values of the Trigonometric Functions 855 G Table: Trigonometric Functions of Large and Small Angles 856 H Powers of Binomials 860 I Derivatives and Integrals of sin θ and cos θ 861 Exercises 863 J.1 Table: Elements and Atomic Weights, Based on Carbon-12 = 12.00000, Alphabetically by Name 864 J.2 Table: The Elements, Alphabetically by Symbol 865 K The de Moivre Theorem 866

ANSWERS TO	PROBLEMS	(Odd Numbers)	868

ANSWERS TO EXERCISES (Odd Numbers) 870

INDEX

ABOUT THE AUTHORS

PIONEERS OF PHYSICS Front inside con	er
--------------------------------------	----

TABLE OF CONSTANTS Back inside cover

TABLE OF INTEGRALSBack inside cover

802