NUS Department of Physics

Syllabus for the Comprehensive Exam

Subject Matter	Exemplary Textbook (defining the scope)	Science Library Call Number
General Physics	Hugh D. Young and Roger A. Freedman, *Sears and Zemansky's University Physics: With Modern Physics*, (12th edition, Pearson Addison Wesley, San Francisco 2008), excluding Chapters 14 and 44	QC23 Sea
Classical Mechanics	Tom W. B. Kibble and Frank H. Berkshire *Classical Mechanics*, (5th edition, Imperial College Press, London 2004), excluding Chapters 12–14	QA845 Tho 2004
Electromagnetism	David J. Griffiths, *Introduction to Electrodynamics*, (3rd edition, Prentice Hall 1999), excluding Chapter 11 and Sections 9.4, 9.5, 10.2.2, and 12.3	QC680 Gri
Quantum Mechanics	David J. Griffiths, *Introduction to Quantum Mechanics*, (Prentice Hall 1995), Chapters 1–7	QC174.12 Gri
Statistical Physics	Franz Mandl, *Statistical Physics*, (2nd edition, Wiley, New York 1988)	QC174.8 Man

Note: These textbook chapters identify the material that is examined in the Comprehensive Exam; the listed textbooks themselves are just examples. The same material is also covered by other books, and all of them can be used equally well when preparing for the exam.

(updated on 07 August 2014)

SEARS AND ZEMANSKY'S

UNIVERSITY PHYSICS

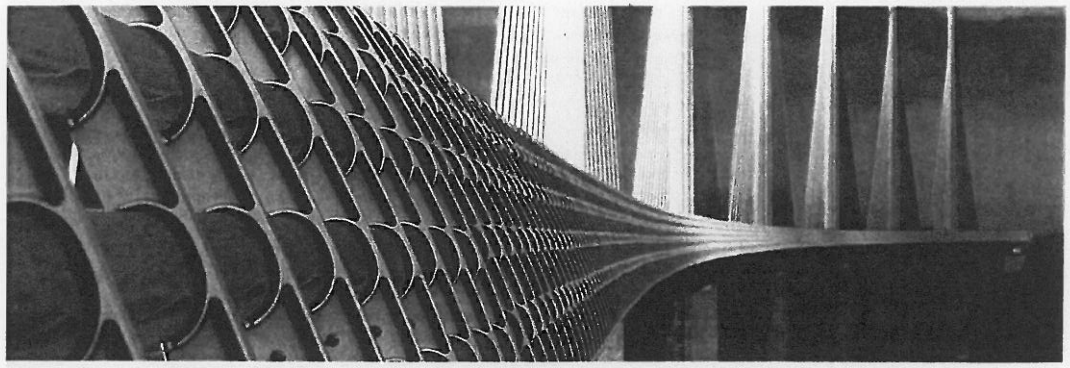
12TH EDITION

WITH MODERN PHYSICS

HUGH D. YOUNG
CARNEGIE MELLON UNIVERSITY

ROGER A. FREEDMAN
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

CONTRIBUTING AUTHOR
A. LEWIS FORD
TEXAS A&M UNIVERSITY



PEARSON
Addison Wesley

San Francisco Boston New York
Cape Town Hong Kong London Madrid Mexico City
Montreal Munich Paris Singapore Sydney Tokyo Toronto

DETAILED CONTENTS

MECHANICS

1 UNITS, PHYSICAL QUANTITIES, AND VECTORS 1

1.1 The Nature of Physics 2
1.2 Solving Physics Problems 2
1.3 Standards and Units 4
1.4 Unit Consistency and Conversions 6
1.5 Uncertainty and Significant Figures 8
1.6 Estimates and Orders of Magnitude 10
1.7 Vectors and Vector Addition 11
1.8 Components of Vectors 15
1.9 Unit Vectors 20
1.10 Products of Vectors 21
Summary/Key Terms 27
Questions/Exercises/Problems 28

2 MOTION ALONG A STRAIGHT LINE 36

2.1 Displacement, Time, and Average Velocity 37
2.2 Instantaneous Velocity 39
2.3 Average and Instantaneous Acceleration 43
2.4 Motion with Constant Acceleration 47
2.5 Freely Falling Bodies 53
*2.6 Velocity and Position by Integration 57
Summary/Key Terms 60
Questions/Exercises/Problems 61

3 MOTION IN TWO OR THREE DIMENSIONS 71

3.1 Position and Velocity Vectors 72
3.2 The Acceleration Vector 74
3.3 Projectile Motion 79
3.4 Motion in a Circle 87
3.5 Relative Velocity 91
Summary/Key Terms 96
Questions/Exercises/Problems 97

4 NEWTON'S LAWS OF MOTION 107

4.1 Force and Interactions 108
4.2 Newton's First Law 111
4.3 Newton's Second Law 115
4.4 Mass and Weight 120
4.5 Newton's Third Law 123
4.6 Free-Body Diagrams 126
Summary/Key Terms 129
Questions/Exercises/Problems 130

5 APPLYING NEWTON'S LAWS 136

5.1 Using Newton's First Law: Particles in Equilibrium 136
5.2 Using Newton's Second Law: Dynamics of Particles 142
5.3 Frictional Forces 149
5.4 Dynamics of Circular Motion 158
*5.5 The Fundamental Forces of Nature 163
Summary/Key Terms 165
Questions/Exercises/Problems 166

6 WORK AND KINETIC ENERGY 181

6.1 Work 182
6.2 Kinetic Energy and the Work–Energy Theorem 186
6.3 Work and Energy with Varying Forces 192
6.4 Power 199
Summary/Key Terms 202
Questions/Exercises/Problems 203

7 POTENTIAL ENERGY AND ENERGY CONSERVATION 213

7.1 Gravitational Potential Energy 214
7.2 Elastic Potential Energy 222
7.3 Conservative and Nonconservative Forces 229
7.4 Force and Potential Energy 232
7.5 Energy Diagrams 235
Summary/Key Terms 237
Questions/Exercises/Problems 238

8 MOMENTUM, IMPULSE, AND COLLISIONS 247

8.1 Momentum and Impulse 247
8.2 Conservation of Momentum 253
8.3 Momentum Conservation and Collisions 257
8.4 Elastic Collisions 262
8.5 Center of Mass 266
*8.6 Rocket Propulsion 270
Summary/Key Terms 273
Questions/Exercises/Problems 274

9 ROTATION OF RIGID BODIES 285

9.1 Angular Velocity and Acceleration 285
9.2 Rotation with Constant Angular Acceleration 290
9.3 Relating Linear and Angular Kinematics 293
9.4 Energy in Rotational Motion 296

9.5 Parallel-Axis Theorem 301
*9.6 Moment-of-Inertia Calculations 303
Summary/Key Terms 306
Questions/Exercises/Problems 307

10 DYNAMICS OF ROTATIONAL MOTION 316
10.1 Torque 316
10.2 Torque and Angular Acceleration for a Rigid Body 319
10.3 Rigid-Body Rotation About a Moving Axis 323
10.4 Work and Power in Rotational Motion 329
10.5 Angular Momentum 331
10.6 Conservation of Angular Momentum 333
10.7 Gyroscopes and Precession 337
Summary/Key Terms 341
Questions/Exercises/Problems 343

11 EQUILIBRIUM AND ELASTICITY 354
11.1 Conditions for Equilibrium 355
11.2 Center of Gravity 355
11.3 Solving Rigid-Body Equilibrium Problems 358
11.4 Stress, Strain, and Elastic Moduli 363
11.5 Elasticity and Plasticity 368
Summary/Key Terms 370
Questions/Exercises/Problems 371

12 GRAVITATION 383
12.1 Newton's Law of Gravitation 383
12.2 Weight 388
12.3 Gravitational Potential Energy 390
12.4 The Motion of Satellites 393
12.5 Kepler's Laws and the Motion of Planets 396
*12.6 Spherical Mass Distributions 400
*12.7 Apparent Weight and the Earth's Rotation 403
12.8 Black Holes 405
Summary/Key Terms 410
Questions/Exercises/Problems 411

13 PERIODIC MOTION 419
13.1 Describing Oscillation 419
13.2 Simple Harmonic Motion 421
13.3 Energy in Simple Harmonic Motion 428
13.4 Applications of Simple Harmonic Motion 432
13.5 The Simple Pendulum 436
13.6 The Physical Pendulum 438
13.7 Damped Oscillations 440
13.8 Forced Oscillations and Resonance 442
Summary/Key Terms 445
Questions/Exercises/Problems 447

14 FLUID MECHANICS 456
14.1 Density 456
14.2 Pressure in a Fluid 458
14.3 Buoyancy 463
14.4 Fluid Flow 466
14.5 Bernoulli's Equation 468
*14.6 Viscosity and Turbulence 472
Summary/Key Terms 476
Questions/Exercises/Problems 477

WAVES/ACOUSTICS

15 MECHANICAL WAVES 487
15.1 Types of Mechanical Waves 488
15.2 Periodic Waves 489
15.3 Mathematical Description of a Wave 492
15.4 Speed of a Transverse Wave 498
15.5 Energy in Wave Motion 502
15.6 Wave Interference, Boundary Conditions, and Superposition 505
15.7 Standing Waves on a String 507
15.8 Normal Modes of a String 511
Summary/Key Terms 516
Questions/Exercises/Problems 518

16 SOUND AND HEARING 527
16.1 Sound Waves 527
16.2 Speed of Sound Waves 532
16.3 Sound Intensity 537
16.4 Standing Sound Waves and Normal Modes 541
16.5 Resonance and Sound 546
16.6 Interference of Waves 548
16.7 Beats 550
16.8 The Doppler Effect 552
*16.9 Shock Waves 558
Summary/Key Terms 561
Questions/Exercises/Problems 563

THERMODYNAMICS

17 TEMPERATURE AND HEAT 570
17.1 Temperature and Thermal Equilibrium 571
17.2 Thermometers and Temperature Scales 572
17.3 Gas Thermometers and the Kelvin Scale 574
17.4 Thermal Expansion 576
17.5 Quantity of Heat 582
17.6 Calorimetry and Phase Changes 586
17.7 Mechanisms of Heat Transfer 591

Summary/Key Terms 598
Questions/Exercises/Problems 600

18 THERMAL PROPERTIES OF MATTER 610
18.1 Equations of State 611
18.2 Molecular Properties of Matter 617
18.3 Kinetic-Molecular Model of an Ideal Gas 619
18.4 Heat Capacities 626
*18.5 Molecular Speeds 629
18.6 Phases of Matter 631
Summary/Key Terms 635
Questions/Exercises/Problems 637

19 THE FIRST LAW OF THERMODYNAMICS 646
19.1 Thermodynamic Systems 646
19.2 Work Done During Volume Changes 647
19.3 Paths Between Thermodynamic States 650
19.4 Internal Energy and the First Law of Thermodynamics 651
19.5 Kinds of Thermodynamic Processes 656
19.6 Internal Energy of an Ideal Gas 658
19.7 Heat Capacities of an Ideal Gas 659
19.8 Adiabatic Processes for an Ideal Gas 662
Summary/Key Terms 665
Questions/Exercises/Problems 667

20 THE SECOND LAW OF THERMODYNAMICS 673
20.1 Directions of Thermodynamic Processes 673
20.2 Heat Engines 675
20.3 Internal-Combustion Engines 678
20.4 Refrigerators 680
20.5 The Second Law of Thermodynamics 682
20.6 The Carnot Cycle 684
20.7 Entropy 690
*20.8 Microscopic Interpretation of Entropy 697
Summary/Key Terms 700
Questions/Exercises/Problems 702

ELECTROMAGNETISM

21 ELECTRIC CHARGE AND ELECTRIC FIELD 709
21.1 Electric Charge 710
21.2 Conductors, Insulators, and Induced Charges 713
21.3 Coulomb's Law 716
21.4 Electric Field and Electric Forces 721
21.5 Electric-Field Calculations 727
21.6 Electric Field Lines 733
21.7 Electric Dipoles 735
Summary/Key Terms 739
Questions/Exercises/Problems 741

22 GAUSS'S LAW 750
22.1 Charge and Electric Flux 750
22.2 Calculating Electric Flux 753
22.3 Gauss's Law 757
22.4 Applications of Gauss's Law 761
22.5 Charges on Conductors 767
Summary/Key Terms 772
Questions/Exercises/Problems 773

23 ELECTRIC POTENTIAL 780
23.1 Electric Potential Energy 780
23.2 Electric Potential 787
23.3 Calculating Electric Potential 794
23.4 Equipotential Surfaces 798
23.5 Potential Gradient 801
Summary/Key Terms 804
Questions/Exercises/Problems 805

24 CAPACITANCE AND DIELECTRICS 815
24.1 Capacitors and Capacitance 816
24.2 Capacitors in Series and Parallel 820
24.3 Energy Storage in Capacitors and Electric-Field Energy 824
24.4 Dielectrics 828
*24.5 Molecular Model of Induced Charge 833
*24.6 Gauss's Law in Dielectrics 835
Summary/Key Terms 837
Questions/Exercises/Problems 838

25 CURRENT, RESISTANCE, AND ELECTROMOTIVE FORCE 846
25.1 Current 847
25.2 Resistivity 850
25.3 Resistance 853
25.4 Electromotive Force and Circuits 857
25.5 Energy and Power in Electric Circuits 863
*25.6 Theory of Metallic Conduction 867
Summary/Key Terms 871
Questions/Exercises/Problems 872

26 DIRECT-CURRENT CIRCUITS 881
26.1 Resistors in Series and Parallel 881
26.2 Kirchhoff's Rules 886
26.3 Electrical Measuring Instruments 891
26.4 *R-C* Circuits 896
26.5 Power Distribution Systems 900

Summary/Key Terms 905
Questions/Exercises/Problems 906

27 MAGNETIC FIELD AND MAGNETIC FORCES 916
27.1 Magnetism 916
27.2 Magnetic Field 918
27.3 Magnetic Field Lines and Magnetic Flux 922
27.4 Motion of Charged Particles in a Magnetic Field 925
27.5 Applications of Motion of Charged Particles 929
27.6 Magnetic Force on a Current-Carrying Conductor 932
27.7 Force and Torque on a Current Loop 935
*27.8 The Direct-Current Motor 941
*27.9 The Hall Effect 943
Summary/Key Terms 945
Questions/Exercises/Problems 947

28 SOURCES OF MAGNETIC FIELD 957
28.1 Magnetic Field of a Moving Charge 957
28.2 Magnetic Field of a Current Element 960
28.3 Magnetic Field of a Straight Current-Carrying Conductor 962
28.4 Force Between Parallel Conductors 965
28.5 Magnetic Field of a Circular Current Loop 967
28.6 Ampere's Law 969
28.7 Applications of Ampere's Law 973
*28.8 Magnetic Materials 976
Summary/Key Terms 982
Questions/Exercises/Problems 984

29 ELECTROMAGNETIC INDUCTION 993
29.1 Induction Experiments 994
29.2 Faraday's Law 996
29.3 Lenz's Law 1004
29.4 Motional Electromotive Force 1006
29.5 Induced Electric Fields 1008
*29.6 Eddy Currents 1011
29.7 Displacement Current and Maxwell's Equations 1013
*29.8 Superconductivity 1017
Summary/Key Terms 1019
Questions/Exercises/Problems 1020

30 INDUCTANCE 1030
30.1 Mutual Inductance 1030
30.2 Self-Inductance and Inductors 1034
30.3 Inductors and Magnetic-Field Energy 1038
30.4 The *R-L* Circuit 1041
30.5 The *L-C* Circuit 1045
30.6 The *L-R-C* Series Circuit 1049
Summary/Key Terms 1052
Questions/Exercises/Problems 1053

31 ALTERNATING CURRENT 1061
31.1 Phasors and Alternating Currents 1061
31.2 Resistance and Reactance 1064
31.3 The *L-R-C* Series Circuit 1070
31.4 Power in Alternating-Current Circuits 1074
31.5 Resonance in Alternating-Current Circuits 1077
31.6 Transformers 1080
Summary/Key Terms 1084
Questions/Exercises/Problems 1085

32 ELECTROMAGNETIC WAVES 1092
32.1 Maxwell's Equations and Electromagnetic Waves 1093
32.2 Plane Electromagnetic Waves and the Speed of Light 1096
32.3 Sinusoidal Electromagnetic Waves 1101
32.4 Energy and Momentum in Electromagnetic Waves 1106
32.5 Standing Electromagnetic Waves 1111
Summary/Key Terms 1115
Questions/Exercises/Problems 1116

OPTICS

33 THE NATURE AND PROPAGATION OF LIGHT 1121
33.1 The Nature of Light 1121
33.2 Reflection and Refraction 1123
33.3 Total Internal Reflection 1129
*33.4 Dispersion 1132
33.5 Polarization 1133
*33.6 Scattering of Light 1142
33.7 Huygens's Principle 1144
Summary/Key Terms 1147
Questions/Exercises/Problems 1149

34 GEOMETRIC OPTICS AND OPTICAL INSTRUMENTS 1157
34.1 Reflection and Refraction at a Plane Surface 1157
34.2 Reflection at a Spherical Surface 1161
34.3 Refraction at a Spherical Surface 1169
34.4 Thin Lenses 1174
34.5 Cameras 1182
34.6 The Eye 1185
34.7 The Magnifier 1189
34.8 Microscopes and Telescopes 1191

Summary/Key Terms 1196
Questions/Exercises/Problems 1198

35 INTERFERENCE 1207
35.1 Interference and Coherent Sources 1208
35.2 Two-Source Interference of Light 1211
35.3 Intensity in Interference Patterns 1214
35.4 Interference in Thin Films 1218
35.5 The Michelson Interferometer 1224
Summary/Key Terms 1227
Questions/Exercises/Problems 1228

36 DIFFRACTION 1234
36.1 Fresnel and Fraunhofer Diffraction 1235
36.2 Diffraction from a Single Slit 1236
36.3 Intensity in the Single-Slit Pattern 1239
36.4 Multiple Slits 1243
36.5 The Diffraction Grating 1246
36.6 X-Ray Diffraction 1250
36.7 Circular Apertures and Resolving Power 1253
*36.8 Holography 1256
Summary/Key Terms 1259
Questions/Exercises/Problems 1260

MODERN PHYSICS

37 RELATIVITY 1268
37.1 Invariance of Physical Laws 1268
37.2 Relativity of Simultaneity 1272
37.3 Relativity of Time Intervals 1274
37.4 Relativity of Length 1278
37.5 The Lorentz Transformation 1283
*37.6 The Doppler Effect for Electromagnetic Waves 1287
37.7 Relativistic Momentum 1289
37.8 Relativistic Work and Energy 1292
37.9 Newtonian Mechanics and Relativity 1295
Summary/Key Terms 1298
Questions/Exercises/Problems 1300

38 PHOTONS, ELECTRONS, AND ATOMS 1307
38.1 Emission and Absorption of Light 1307
38.2 The Photoelectric Effect 1309
38.3 Atomic Line Spectra and Energy Levels 1314
38.4 The Nuclear Atom 1319
38.5 The Bohr Model 1322
38.6 The Laser 1327
38.7 X-Ray Production and Scattering 1330
38.8 Continuous Spectra 1334
38.9 Wave–Particle Duality 1338
Summary/Key Terms 1340
Questions/Exercises/Problems 1342

39 THE WAVE NATURE OF PARTICLES 1349
39.1 De Broglie Waves 1350
39.2 Electron Diffraction 1352
39.3 Probability and Uncertainty 1355
39.4 The Electron Microscope 1360
39.5 Wave Functions and the Schrödinger Equation 1361
Summary/Key Terms 1368
Questions/Exercises/Problems 1369

40 QUANTUM MECHANICS 1375
40.1 Particle in a Box 1375
40.2 Potential Wells 1380
40.3 Potential Barriers and Tunneling 1384
40.4 The Harmonic Oscillator 1387
40.5 Three-Dimensional Problems 1392
Summary/Key Terms 1394
Questions/Exercises/Problems 1395

41 ATOMIC STRUCTURE 1401
41.1 The Hydrogen Atom 1401
41.2 The Zeeman Effect 1409
41.3 Electron Spin 1413
41.4 Many-Electron Atoms and the Exclusion Principle 1417
41.5 X-Ray Spectra 1423
Summary/Key Terms 1427
Questions/Exercises/Problems 1428

42 MOLECULES AND CONDENSED MATTER 1433
42.1 Types of Molecular Bonds 1433
42.2 Molecular Spectra 1436
42.3 Structure of Solids 1441
42.4 Energy Bands 1445
42.5 Free-Electron Model of Metals 1447
42.6 Semiconductors 1452
42.7 Semiconductor Devices 1455
42.8 Superconductivity 1460
Summary/Key Terms 1461
Questions/Exercises/Problems 1462

43 NUCLEAR PHYSICS 1468
43.1 Properties of Nuclei 1468
43.2 Nuclear Binding and Nuclear Structure 1473

43.3 Nuclear Stability and Radioactivity 1478
43.4 Activities and Half-Lives 1485
43.5 Biological Effects of Radiation 1489
43.6 Nuclear Reactions 1492
43.7 Nuclear Fission 1494
43.8 Nuclear Fusion 1498
Summary/Key Terms 1502
Questions/Exercises/Problems 1503

44 PARTICLE PHYSICS AND COSMOLOGY 1509

44.1 Fundamental Particles—A History 1509
44.2 Particle Accelerators and Detectors 1514
44.3 Particles and Interactions 1519
44.4 Quarks and the Eightfold Way 1525
44.5 The Standard Model and Beyond 1530
44.6 The Expanding Universe 1532
44.7 The Beginning of Time 1538
Summary/Key Terms 1547
Questions/Exercises/Problems 1548

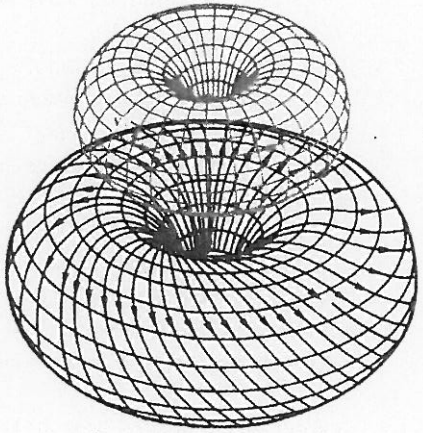
APPENDICES

A The International System of Units A-1
B Useful Mathematical Relations A-3
C The Greek Alphabet A-4
D Periodic Table of Elements A-5
E Unit Conversion Factors A-6
F Numerical Constants A-7

Answers to Odd-Numbered Problems A-9
Photo Credits C-1
Index I-1

CLASSICAL MECHANICS

5th Edition



Tom W.B. Kibble
Frank H. Berkshire
Imperial College London

ICP
Imperial College Press

Contents

Preface vii

Useful Constants and Units xv

List of Symbols xvii

1. Introduction 1
   - 1.1 Space and Time . . . 2
   - 1.2 Newton's Laws . . . 5
   - 1.3 The Concepts of Mass and Force . . . 10
   - 1.4 External Forces . . . 13
   - 1.5 Summary . . . 13

2. Linear Motion 17
   - 2.1 Conservative Forces; Conservation of Energy . . . 17
   - 2.2 Motion near Equilibrium; the Harmonic Oscillator . . . 20
   - 2.3 Complex Representation . . . 24
   - 2.4 The Law of Conservation of Energy . . . 25
   - 2.5 The Damped Oscillator . . . 27
   - 2.6 Oscillator under Simple Periodic Force . . . 30
   - 2.7 General Periodic Force . . . 34
   - 2.8 Impulsive Forces; the Green's Function Method . . . 37
   - 2.9 Collision Problems . . . 39
   - 2.10 Summary . . . 42

3. Energy and Angular Momentum 49
3.1 Energy; Conservative Forces . . . 49
3.2 Projectiles . . . 51
3.3 Moments; Angular Momentum . . . 53
3.4 Central Forces; Conservation of Angular Momentum . . . 55
3.5 Polar Co-ordinates . . . 57
3.6 The Calculus of Variations . . . 59
3.7 Hamilton's Principle; Lagrange's Equations . . . 62
3.8 Summary . . . 66

4. Central Conservative Forces 73
4.1 The Isotropic Harmonic Oscillator . . . 73
4.2 The Conservation Laws . . . 76
4.3 The Inverse Square Law . . . 78
4.4 Orbits . . . 84
4.5 Scattering Cross-sections . . . 90
4.6 Mean Free Path . . . 94
4.7 Rutherford Scattering . . . 96
4.8 Summary . . . 98

5. Rotating Frames 105
5.1 Angular Velocity; Rate of Change of a Vector . . . 105
5.2 Particle in a Uniform Magnetic Field . . . 108
5.3 Acceleration; Apparent Gravity . . . 111
5.4 Coriolis Force . . . 114
5.5 Larmor Effect . . . 120
5.6 Angular Momentum and the Larmor Effect . . . 121
5.7 Summary . . . 124

6. Potential Theory 129
6.1 Gravitational and Electrostatic Potentials . . . 129
6.2 The Dipole and Quadrupole . . . 131
6.3 Spherical Charge Distributions . . . 134
6.4 Expansion of Potential at Large Distances . . . 137
6.5 The Shape of the Earth . . . 140
6.6 The Tides . . . 144
6.7 The Field Equations . . . 148
6.8 Summary . . . 152

7. The Two-Body Problem 159
7.1 Centre-of-mass and Relative Co-ordinates . . . 159
7.2 The Centre-of-mass Frame . . . 162
7.3 Elastic Collisions . . . 165
7.4 CM and Lab Cross-sections . . . 168
7.5 Summary . . . 173

8. Many-Body Systems 177
8.1 Momentum; Centre-of-mass Motion . . . 177
8.2 Angular Momentum; Central Internal Forces . . . 181
8.3 The Earth–Moon System . . . 183
8.4 Energy; Conservative Forces . . . 188
8.5 Lagrange's Equations . . . 190
8.6 Summary . . . 192

9. Rigid Bodies 197
9.1 Basic Principles . . . 197
9.2 Rotation about an Axis . . . 198
9.3 Perpendicular Components of Angular Momentum . . . 203
9.4 Principal Axes of Inertia . . . 205
9.5 Calculation of Moments of Inertia . . . 208
9.6 Effect of a Small Force on the Axis . . . 211
9.7 Instantaneous Angular Velocity . . . 216
9.8 Rotation about a Principal Axis . . . 218
9.9 Euler's Angles . . . 221
9.10 Summary . . . 225

10. Lagrangian Mechanics 231
10.1 Generalized Co-ordinates; Holonomic Systems . . . 231
10.2 Lagrange's Equations . . . 233
10.3 Precession of a Symmetric Top . . . 236
10.4 Pendulum Constrained to Rotate about an Axis . . . 238
10.5 Charged Particle in an Electromagnetic Field . . . 241
10.6 The Stretched String . . . 244
10.7 Summary . . . 248

11. Small Oscillations and Normal Modes 253
11.1 Orthogonal Co-ordinates . . . 253

11.2 Equations of Motion for Small Oscillations 256
11.3 Normal Modes 258
11.4 Coupled Oscillators 261
11.5 Oscillations of Particles on a String 266
11.6 Normal Modes of a Stretched String 269
11.7 Summary 272

12. Hamiltonian Mechanics 277

12.1 Hamilton's Equations 277
12.2 Conservation of Energy 280
12.3 Ignorable Co-ordinates 282
12.4 General Motion of the Symmetric Top 285
12.5 Liouville's Theorem 289
12.6 Symmetries and Conservation Laws 291
12.7 Galilean Transformations 295
12.8 Summary 300

13. Dynamical Systems and Their Geometry 307

13.1 Phase Space and Phase Portraits 307
13.2 First-order Systems — the Phase Line ($n = 1$) 309
13.3 Second-order Systems — the Phase Plane ($n = 2$) 312
13.4 Prey–Predator, Competing-species Systems and War . . 318
13.5 Limit Cycles 324
13.6 Systems of Third (and Higher) Order 329
13.7 Sensitivity to Initial Conditions and Predictability 337
13.8 Summary 340

14. Order and Chaos in Hamiltonian Systems 347

14.1 Integrability 347
14.2 Surfaces of Section 351
14.3 Action/Angle Variables 354
14.4 Some Hamiltonian Systems which Exhibit Chaos 359
14.5 Slow Change of Parameters — Adiabatic Invariance . . . 369
14.6 Near-integrable Systems 372
14.7 Summary 374

Appendix A. Vectors 381

A.1 Definitions and Elementary Properties 381

A.2 The Scalar Product 384
A.3 The Vector Product 385
A.4 Differentiation and Integration of Vectors 388
A.5 Gradient, Divergence and Curl 390
A.6 Integral Theorems 393
A.7 Electromagnetic Potentials 397
A.8 Curvilinear Co-ordinates 398
A.9 Tensors 401
A.10 Eigenvalues; Diagonalization of a Symmetric Tensor . . . 403

Appendix B. Conics 409

B.1 Cartesian Form 409
B.2 Polar Form 412

Appendix C. Phase Plane Analysis near Critical Points 415

C.1 Linear Systems and their Classification 415
C.2 Almost Linear Systems 421
C.3 Systems of Third (and Higher) Order 423

Appendix D. Discrete Dynamical Systems — Maps 425

D.1 One-dimensional Maps 425
D.2 Two-dimensional Maps 433
D.3 Twist Maps and Torus Breakdown 437

Answers to Problems 445

Bibliography 463

Index 465

Introduction to Electrodynamics

David J. Griffiths
Reed College

(3rd edition)

PEARSON
Benjamin Cummings

San Francisco Boston New York
Cape Town Hong Kong London Madrid Mexico City
Montreal Munich Paris Singapore Sydney Tokyo Toronto

Contents

Preface ix

Advertisement xi

1 Vector Analysis 1
1.1 Vector Algebra . . . 1
1.1.1 Vector Operations . . . 1
1.1.2 Vector Algebra: Component Form . . . 4
1.1.3 Triple Products . . . 7
1.1.4 Position, Displacement, and Separation Vectors . . . 8
1.1.5 How Vectors Transform . . . 10
1.2 Differential Calculus . . . 13
1.2.1 "Ordinary" Derivatives . . . 13
1.2.2 Gradient . . . 13
1.2.3 The Operator ∇ . . . 16
1.2.4 The Divergence . . . 17
1.2.5 The Curl . . . 19
1.2.6 Product Rules . . . 20
1.2.7 Second Derivatives . . . 22
1.3 Integral Calculus . . . 24
1.3.1 Line, Surface, and Volume Integrals . . . 24
1.3.2 The Fundamental Theorem of Calculus . . . 28
1.3.3 The Fundamental Theorem for Gradients . . . 29
1.3.4 The Fundamental Theorem for Divergences . . . 31
1.3.5 The Fundamental Theorem for Curls . . . 34
1.3.6 Integration by Parts . . . 37
1.4 Curvilinear Coordinates . . . 38
1.4.1 Spherical Polar Coordinates . . . 38
1.4.2 Cylindrical Coordinates . . . 43
1.5 The Dirac Delta Function . . . 45
1.5.1 The Divergence of $\hat{\mathbf{r}}/r^2$ . . . 45
1.5.2 The One-Dimensional Dirac Delta Function . . . 46

1.5.3 The Three-Dimensional Delta Function . . . 50
1.6 The Theory of Vector Fields . . . 52
1.6.1 The Helmholtz Theorem . . . 52
1.6.2 Potentials . . . 53

2 Electrostatics **58**
2.1 The Electric Field . . . 58
2.1.1 Introduction . . . 58
2.1.2 Coulomb's Law . . . 59
2.1.3 The Electric Field . . . 60
2.1.4 Continuous Charge Distributions . . . 61
2.2 Divergence and Curl of Electrostatic Fields . . . 65
2.2.1 Field Lines, Flux, and Gauss's Law . . . 65
2.2.2 The Divergence of E . . . 69
2.2.3 Applications of Gauss's Law . . . 70
2.2.4 The Curl of E . . . 76
2.3 Electric Potential . . . 77
2.3.1 Introduction to Potential . . . 77
2.3.2 Comments on Potential . . . 79
2.3.3 Poisson's Equation and Laplace's Equation . . . 83
2.3.4 The Potential of a Localized Charge Distribution . . . 83
2.3.5 Summary; Electrostatic Boundary Conditions . . . 87
2.4 Work and Energy in Electrostatics . . . 90
2.4.1 The Work Done to Move a Charge . . . 90
2.4.2 The Energy of a Point Charge Distribution . . . 91
2.4.3 The Energy of a Continuous Charge Distribution . . . 93
2.4.4 Comments on Electrostatic Energy . . . 95
2.5 Conductors . . . 96
2.5.1 Basic Properties . . . 96
2.5.2 Induced Charges . . . 98
2.5.3 Surface Charge and the Force on a Conductor . . . 102
2.5.4 Capacitors . . . 103

3 Special Techniques **110**
3.1 Laplace's Equation . . . 110
3.1.1 Introduction . . . 110
3.1.2 Laplace's Equation in One Dimension . . . 111
3.1.3 Laplace's Equation in Two Dimensions . . . 112
3.1.4 Laplace's Equation in Three Dimensions . . . 114
3.1.5 Boundary Conditions and Uniqueness Theorems . . . 116
3.1.6 Conductors and the Second Uniqueness Theorem . . . 118
3.2 The Method of Images . . . 121
3.2.1 The Classic Image Problem . . . 121
3.2.2 Induced Surface Charge . . . 123

3.2.3 Force and Energy . . . 123
3.2.4 Other Image Problems . . . 124
3.3 Separation of Variables . . . 127
3.3.1 Cartesian Coordinates . . . 127
3.3.2 Spherical Coordinates . . . 137
3.4 Multipole Expansion . . . 146
3.4.1 Approximate Potentials at Large Distances . . . 146
3.4.2 The Monopole and Dipole Terms . . . 149
3.4.3 Origin of Coordinates in Multipole Expansions . . . 151
3.4.4 The Electric Field of a Dipole . . . 153

4 Electric Fields in Matter **160**
4.1 Polarization . . . 160
4.1.1 Dielectrics . . . 160
4.1.2 Induced Dipoles . . . 160
4.1.3 Alignment of Polar Molecules . . . 163
4.1.4 Polarization . . . 166
4.2 The Field of a Polarized Object . . . 166
4.2.1 Bound Charges . . . 166
4.2.2 Physical Interpretation of Bound Charges . . . 170
4.2.3 The Field Inside a Dielectric . . . 173
4.3 The Electric Displacement . . . 175
4.3.1 Gauss's Law in the Presence of Dielectrics . . . 175
4.3.2 A Deceptive Parallel . . . 178
4.3.3 Boundary Conditions . . . 178
4.4 Linear Dielectrics . . . 179
4.4.1 Susceptibility, Permittivity, Dielectric Constant . . . 179
4.4.2 Boundary Value Problems with Linear Dielectrics . . . 186
4.4.3 Energy in Dielectric Systems . . . 191
4.4.4 Forces on Dielectrics . . . 193

5 Magnetostatics **202**
5.1 The Lorentz Force Law . . . 202
5.1.1 Magnetic Fields . . . 202
5.1.2 Magnetic Forces . . . 204
5.1.3 Currents . . . 208
5.2 The Biot-Savart Law . . . 215
5.2.1 Steady Currents . . . 215
5.2.2 The Magnetic Field of a Steady Current . . . 215
5.3 The Divergence and Curl of B . . . 221
5.3.1 Straight-Line Currents . . . 221
5.3.2 The Divergence and Curl of B . . . 222
5.3.3 Applications of Ampère's Law . . . 225
5.3.4 Comparison of Magnetostatics and Electrostatics . . . 232

5.4 Magnetic Vector Potential 234
5.4.1 The Vector Potential 234
5.4.2 Summary; Magnetostatic Boundary Conditions 240
5.4.3 Multipole Expansion of the Vector Potential 242

6 Magnetic Fields in Matter **255**
6.1 Magnetization 255
6.1.1 Diamagnets, Paramagnets, Ferromagnets 255
6.1.2 Torques and Forces on Magnetic Dipoles 255
6.1.3 Effect of a Magnetic Field on Atomic Orbits 260
6.1.4 Magnetization 262
6.2 The Field of a Magnetized Object 263
6.2.1 Bound Currents 263
6.2.2 Physical Interpretation of Bound Currents 266
6.2.3 The Magnetic Field Inside Matter 268
6.3 The Auxiliary Field H 269
6.3.1 Ampère's law in Magnetized Materials 269
6.3.2 A Deceptive Parallel 273
6.3.3 Boundary Conditions 273
6.4 Linear and Nonlinear Media 274
6.4.1 Magnetic Susceptibility and Permeability 274
6.4.2 Ferromagnetism 278

7 Electrodynamics **285**
7.1 Electromotive Force 285
7.1.1 Ohm's Law 285
7.1.2 Electromotive Force 292
7.1.3 Motional emf 294
7.2 Electromagnetic Induction 301
7.2.1 Faraday's Law 301
7.2.2 The Induced Electric Field 305
7.2.3 Inductance 310
7.2.4 Energy in Magnetic Fields 317
7.3 Maxwell's Equations 321
7.3.1 Electrodynamics Before Maxwell 321
7.3.2 How Maxwell Fixed Ampère's Law 323
7.3.3 Maxwell's Equations 326
7.3.4 Magnetic Charge 327
7.3.5 Maxwell's Equations in Matter 328
7.3.6 Boundary Conditions 331

8 Conservation Laws **345**
8.1 Charge and Energy 345
8.1.1 The Continuity Equation 345
8.1.2 Poynting's Theorem 346
8.2 Momentum 349
8.2.1 Newton's Third Law in Electrodynamics 349
8.2.2 Maxwell's Stress Tensor 351
8.2.3 Conservation of Momentum 355
8.2.4 Angular Momentum 358

9 Electromagnetic Waves **364**
9.1 Waves in One Dimension 364
9.1.1 The Wave Equation 364
9.1.2 Sinusoidal Waves 367
9.1.3 Boundary Conditions: Reflection and Transmission 370
9.1.4 Polarization 373
9.2 Electromagnetic Waves in Vacuum 375
9.2.1 The Wave Equation for **E** and **B** 375
9.2.2 Monochromatic Plane Waves 376
9.2.3 Energy and Momentum in Electromagnetic Waves 380
9.3 Electromagnetic Waves in Matter 382
9.3.1 Propagation in Linear Media 382
9.3.2 Reflection and Transmission at Normal Incidence 384
9.3.3 Reflection and Transmission at Oblique Incidence 386
9.4 Absorption and Dispersion 392
9.4.1 Electromagnetic Waves in Conductors 392
9.4.2 Reflection at a Conducting Surface 396
9.4.3 The Frequency Dependence of Permittivity 398
9.5 Guided Waves 405
9.5.1 Wave Guides 405
9.5.2 TE Waves in a Rectangular Wave Guide 408
9.5.3 The Coaxial Transmission Line 411

10 Potentials and Fields **416**
10.1 The Potential Formulation 416
10.1.1 Scalar and Vector Potentials 416
10.1.2 Gauge Transformations 419
10.1.3 Coulomb Gauge and Lorentz* Gauge 421
10.2 Continuous Distributions 422
10.2.1 Retarded Potentials 422
10.2.2 Jefimenko's Equations 427
10.3 Point Charges 429
10.3.1 Liénard-Wiechert Potentials 429
10.3.2 The Fields of a Moving Point Charge 435

11 Radiation **443**
11.1 Dipole Radiation 443
11.1.1 What is Radiation? 443
11.1.2 Electric Dipole Radiation 444
11.1.3 Magnetic Dipole Radiation 451
11.1.4 Radiation from an Arbitrary Source 454
11.2 Point Charges 460
11.2.1 Power Radiated by a Point Charge 460
11.2.2 Radiation Reaction 465
11.2.3 The Physical Basis of the Radiation Reaction 469

12 Electrodynamics and Relativity **477**
12.1 The Special Theory of Relativity 477
12.1.1 Einstein's Postulates 477
12.1.2 The Geometry of Relativity 483
12.1.3 The Lorentz Transformations 493
12.1.4 The Structure of Spacetime 500
12.2 Relativistic Mechanics 507
12.2.1 Proper Time and Proper Velocity 507
12.2.2 Relativistic Energy and Momentum 509
12.2.3 Relativistic Kinematics 511
12.2.4 Relativistic Dynamics 516
12.3 Relativistic Electrodynamics 522
12.3.1 Magnetism as a Relativistic Phenomenon 522
12.3.2 How the Fields Transform 525
12.3.3 The Field Tensor 535
12.3.4 Electrodynamics in Tensor Notation 537
12.3.5 Relativistic Potentials 541

A Vector Calculus in Curvilinear Coordinates **547**
A.1 Introduction 547
A.2 Notation 547
A.3 Gradient 548
A.4 Divergence 549
A.5 Curl 552
A.6 Laplacian 554

B The Helmholtz Theorem **555**

C Units **558**

Index **562**

Introduction to Quantum Mechanics

David J. Griffiths
Reed College

Prentice Hall
Upper Saddle River, New Jersey 07458

CONTENTS

PREFACE, vii

PART I
THEORY

CHAPTER 1
THE WAVE FUNCTION, 1

1.1 The Schrodinger Equation, 1
1.2 The Statistical Interpretation, 2
1.3 Probability, 5
1.4 Normalization, 11
1.5 Momentum, 14
1.6 The Uncertainty Principle, 17

CHAPTER 2
THE TIME-INDEPENDENT SCHRODINGER EQUATION, 20

2.1 Stationary States, 20
2.2 The Infinite Square Well, 24
2.3 The Harmonic Oscillator, 31
2.4 The Free Particle, 44
2.5 The Delta-Function Potential, 50
2.6 The Finite Square Well, 60

2.7 The Scattering Matrix, 66
Further Problems for Chapter 2, 68

CHAPTER 3
FORMALISM, 75

3.1 Linear Algebra, 75
3.2 Function Spaces, 95
3.3 The Generalized Statistical Interpretation, 104
3.4 The Uncertainty Principle, 108
Further Problems for Chapter 3, 116

CHAPTER 4
QUANTUM MECHANICS IN THREE DIMENSIONS, 121

4.1 Schrodinger Equations in Spherical Coordinates, 121
4.2 The Hydrogen Atom, 133
4.3 Angular Momentum, 145
4.4 Spin, 154
Further Problems for Chapter 4, 170

CHAPTER 5
IDENTICAL PARTICLES, 177

5.1 Two-Particle Systems, 177
5.2 Atoms, 186
5.3 Solids, 193
5.4 Quantum Statistical Mechanics, 204
Further Problems for Chapter 5, 218

PART II
APPLICATIONS

CHAPTER 6
TIME-INDEPENDENT PERTURBATION THEORY, 221

6.1 Nondegenerate Perturbation Theory, 221
6.2 Degenerate Perturbation Theory, 227
6.3 The Fine Structure of Hydrogen, 235
6.4 The Zeeman Effect, 244
6.5 Hyperfined Splitting, 250
Further Problems for Chapter 6, 252

CHAPTER 7
THE VARIATIONAL PRINCIPLE, 256

7.1 Theory, 256
7.2 The Ground State of Helium, 261
7.3 The Hydrogen Molecule Ion, 266
Further Problems for Chapter 7, 271

CHAPTER 8
THE WKB APPROXIMATION, 274

8.1 The "Classical" Region, 275
8.2 Tunneling, 280
8.3 The Connection Formulas, 284
Further Problems for Chapter 8, 293

CHAPTER 9
TIME-DEPENDENT PERTURBATION THEORY, 298

9.1 Two-Level Systems, 299
9.2 Emission and Absorption of Radiation, 306
9.3 Spontaneous Emission, 311
Further Problems for Chapter 9, 319

CHAPTER 10
THE ADIABATIC APPROXIMATION, 323

10.1 The Adiabatic Theorem, 323
10.2 Berry's Phase, 333
Further Problems for Chapter 10, 349

CHAPTER 11
SCATTERING, 352

11.1 Introduction, 352
11.2 Partial Wave Analysis, 357
11.3 The Born Approximation, 363
Further Problems for Chapter 11, 373

AFTERWORD, 374

INDEX, 386

F. Mandl

Statistical Physics

(2nd edition)

Contents

Flow diagram inside front cover

1 THE FIRST LAW OF THERMODYNAMICS

1.1 Macroscopic Physics 1
1.2 Some Thermal Concepts. 4
1.3 The First Law. 10
★ 1.4 Magnetic Work 21
Summary 28
PROBLEMS 1 29

2 THE SECOND LAW OF THERMODYNAMICS I

2.1 The Direction of Natural Processes. 31
2.2 The Statistical Weight of a Macrostate 34
2.3 Equilibrium of an Isolated System 40
2.4 The Schottky Defect 48
2.5 Equilibrium of a System in a Heat Bath. 52
Summary 64
PROBLEMS 2 66

3 PARAMAGNETISM

3.1 A Paramagnetic Solid in a Heat Bath 68

★ Starred sections may be omitted as they are not required later in the book.

★ 3.2 The Heat Capacity and the Entropy. 75
★ 3.3 An Isolated Paramagnetic Solid 77
★ 3.4 Negative Temperature 78
PROBLEMS 3 81

4 THE SECOND LAW OF THERMODYNAMICS II

4.1 The Second Law for Infinitesimal Changes . . 83
4.2 The Clausius Inequality 89
4.3 Simple Applications 92
4.3.1 Heating Water 93
4.3.2 Melting Ice 94
4.3.3 Temperature Equalization 94
4.3.4 Isothermal Compression of a Perfect Gas . . 95
4.4 The Helmholtz Free Energy 97
4.5 Other Thermodynamic Potentials 99
★ 4.6 Maximum Work 102
4.7 The Third Law of Thermodynamics. 105
★ 4.8 The Third Law (continued) 109
Summary 111
PROBLEMS 4 113

5 SIMPLE THERMODYNAMIC SYSTEMS

★ 5.1 Other Forms of the Second Law 115
★ 5.2 Heat Engines and Refrigerators 117
★ 5.3 The Difference of Heat Capacities 123
★ 5.4 Some Properties of Perfect Gases 125
5.4.1 The Entropy 125
5.4.2 The Entropy of Mixing. 126
★ 5.5 Some Properties of Real Gases. 130
5.5.1 The Joule Effect 130
5.5.2 The Joule–Thomson Effect 132
5.5.3 The Counter–Current Heat Exchanger. . . 137
★ 5.6 Adiabatic cooling 139
PROBLEMS 5 145

6 THE HEAT CAPACITY OF SOLIDS

6.1 Introductory Remarks 147
6.2 Einstein's Theory 149
6.2.1 Derivation of Einstein's Result 149
6.2.2 Comparison of Einstein's Result with Experiment . 155
★ 6.3 Debye's Theory 157

6.3.1 Derivation of Debye's Result 157
6.3.2 Comparison of Debye's Result with Experiment . 162
PROBLEMS 6 164

7 THE PERFECT CLASSICAL GAS

7.1 The Definition of the Perfect Classical Gas . . . 166
7.2 The Partition Function 169
7.3 Validity Criterion for the Classical Regime . . . 175
7.4 The Equation of State 178
★ 7.5 The Heat Capacity 179
★ 7.6 The Entropy 181
★ 7.7 The Maxwell Velocity Distribution 184
★ 7.8 Real Gases 191
★ 7.9 Classical Statistical Mechanics 204
7.9.1 The Equipartition of Energy 210
PROBLEMS 7 214

8 PHASE EQUILIBRIA

8.1 Equilibrium Conditions 218
★ 8.2 Alternative Derivation of the Equilibrium Conditions . 221
8.3 Discussion of the Equilibrium Conditions . . . 223
8.4 The Clausius–Clapeyron Equation 226
8.5 Applications of the Clausius–Clapeyron Equation . 230
8.5.1 Pressure Dependence of the Melting Point . 230
8.5.2 Pressure Dependence of the Boiling Point . 231
8.5.3 The Vapour Pressure Curve 231
★ 8.6 The Critical Point 232
PROBLEMS 8 237

9 THE PERFECT QUANTAL GAS

9.1 Introductory Remarks 239
9.2 Quantum Statistics 240
9.3 The Partition Function 244
PROBLEMS 9 245

10 BLACK-BODY RADIATION

10.1 Introductory Remarks 246
10.2 The Partition Function for Photons 247
10.3 Planck's Law: Derivation 249
10.4 The Properties of Black-Body Radiation . . . 251
★ 10.5 The Thermodynamics of Black-Body Radiation . . 256
PROBLEMS 10 259

11 SYSTEMS WITH VARIABLE PARTICLE NUMBERS

11.1 The Gibbs Distribution* 261
11.2 The FD and BE Distributions* 265
★ 11.2.1 Fluctuations in a Perfect Gas 270
★ 11.3 The FD and BE Distributions: Alternative Approach* . 272
★ 11.4 The Classical Limit 281
★ 11.5 The Free Electron Model of Metals 283
11.5.1 The Fermi–Dirac Energy Distribution . . . 284
11.5.2 The Electronic Heat Capacity of Metals . . 290
★ 11.6 Bose–Einstein Condensation 292
11.7 Thermodynamics of the Gibbs Distribution . . . 299
★ 11.7.1 Fluctuations of Particle Numbers . . . 301
★ 11.8 The Perfect Classical Gas 303
11.9 Chemical Reactions 304
11.9.1 Conditions for Chemical Equilibrium . . 305
11.9.2 Law of Mass Action 307
11.9.3 Heat of Reaction 310
11.9.4 Pressure Dependence of the Reaction Equilibrium . 313
PROBLEMS 11 314

A MATHEMATICAL RESULTS

A.1 Stirling's Formula 317
A.2 Evaluation of $\int_0^\infty (e^x - 1)^{-1} x^3 \, dx$ 318
A.3 Some Kinetic Theory Integrals 321

B THE DENSITY OF STATES

B.1 The General Case 324
B.2 The Schrödinger Equation 331
B.3 Electromagnetic Waves 332
B.4 Elastic Waves in a Continuous Solid 333

C MAGNETIC SYSTEMS 336

D HINTS FOR SOLVING PROBLEMS 340

Bibliography 374
Index 379
Physical constants and conversion factors inside back cover

*Sections 11.1–11.2 and section 11.3 are alternative treatments which can be read independently of each other. Either suffices for the applications in sections 11.4 to 11.6. Sections 11.7 to 11.9 depend on section 11.1 only.