## NUS Department of Physics

### Syllabus for the Comprehensive Exam

<table>
<thead>
<tr>
<th>Subject</th>
<th>Exemplary Textbook (defining the scope)</th>
<th>Science Library Call Number</th>
</tr>
</thead>
</table>

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)
14 FLUID MECHANICS 456

14.1 Density 456
14.2 Pressure in a Fluid 458
14.3 Buoyancy 461
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

15 WAVES/ACOUSTICS 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 555
Summary/Key Terms 561
Questions/Exercises/Problems 563

17 THERMODYNAMICS 570

17.1 Temperature and Thermodynamic 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

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 *18.5 Molecular Speeds 620
18.6 Phases of Matter 620
Summary/Key Terms 631
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 Definitions 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

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

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 855
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
31 ALTERNATING CURRENT 1061

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

32 ELECTROMAGNETIC WAVES 1092

32.1 Maxwell's Equations 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

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 Huygen'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

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 1249
36.7 Circular Apertures and Resolving Power 1253
*36.8 Holography 1256
Summary/Key Terms 1259
Questions/Exercises/Problems 1260

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 1279
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

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-Atom 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
## Detailed Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.3 Nuclear Stability and Radioactivity</td>
<td>1478</td>
</tr>
<tr>
<td>43.4 Activities and Half-Lives</td>
<td>1485</td>
</tr>
<tr>
<td>43.5 Biological Effects of Radiation</td>
<td>1489</td>
</tr>
<tr>
<td>43.6 Nuclear Reactions</td>
<td>1492</td>
</tr>
<tr>
<td>43.7 Nuclear Fusion</td>
<td>1494</td>
</tr>
<tr>
<td>43.8 Nuclear Fusion</td>
<td>1498</td>
</tr>
<tr>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>Questions/Exercises/Problems</td>
<td>1503</td>
</tr>
</tbody>
</table>

### PARTICLE PHYSICS AND COSMOLOGY

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>44.1 Fundamental Particles—A History</td>
<td>1509</td>
</tr>
<tr>
<td>44.2 Particle Accelerators and Detectors</td>
<td>1514</td>
</tr>
<tr>
<td>44.3 Particles and Interactions</td>
<td>1519</td>
</tr>
<tr>
<td>44.4 Quarks and the Eightfold Way</td>
<td>1523</td>
</tr>
<tr>
<td>44.5 The Standard Model and Beyond</td>
<td>1530</td>
</tr>
<tr>
<td>44.6 The Expanding Universe</td>
<td>1532</td>
</tr>
</tbody>
</table>

### APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A The International System of Units</td>
<td>A-1</td>
</tr>
<tr>
<td>B Useful Mathematical Relations</td>
<td>A-3</td>
</tr>
<tr>
<td>C The Greek Alphabet</td>
<td>A-4</td>
</tr>
<tr>
<td>D Periodic Table of Elements</td>
<td>A-5</td>
</tr>
<tr>
<td>E Unit Conversion Factors</td>
<td>A-6</td>
</tr>
<tr>
<td>F Numerical Constants</td>
<td>A-7</td>
</tr>
<tr>
<td>Answers to Odd-Numbered Problems</td>
<td>A-9</td>
</tr>
<tr>
<td>Photo Credits</td>
<td>C-1</td>
</tr>
<tr>
<td>Index</td>
<td>1-1</td>
</tr>
</tbody>
</table>
# Contents

*Preface*  
*Useful Constants and Units*  
*List of Symbols*  

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

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

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
### Contents

7. The Two-Body Problem
   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
   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
   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
    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
    11.1 Orthogonal Co-ordinates ................. 253
### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.2 The Scalar Product</td>
<td>384</td>
</tr>
<tr>
<td>A.3 The Vector Product</td>
<td>385</td>
</tr>
<tr>
<td>A.4 Differentiation and Integration of Vectors</td>
<td>388</td>
</tr>
<tr>
<td>A.5 Gradient, Divergence and Curl</td>
<td>390</td>
</tr>
<tr>
<td>A.6 Integral Theorems</td>
<td>393</td>
</tr>
<tr>
<td>A.7 Electromagnetic Potentials</td>
<td>397</td>
</tr>
<tr>
<td>A.8 Curvilinear Co-ordinates</td>
<td>398</td>
</tr>
<tr>
<td>A.9 Tensors</td>
<td>401</td>
</tr>
<tr>
<td>A.10 Eigenvalues, Diagonalization of a Symmetric Tensor</td>
<td>403</td>
</tr>
<tr>
<td>Appendix B. Conics</td>
<td></td>
</tr>
<tr>
<td>B.1 Cartesian Form</td>
<td>409</td>
</tr>
<tr>
<td>B.2 Polar Form</td>
<td>412</td>
</tr>
<tr>
<td>Appendix C. Phase Plane Analysis near Critical Points</td>
<td>415</td>
</tr>
<tr>
<td>C.1 Linear Systems and their Classification</td>
<td>415</td>
</tr>
<tr>
<td>C.2 Almost Linear Systems</td>
<td>421</td>
</tr>
<tr>
<td>C.3 Systems of Third (and Higher) Order</td>
<td>423</td>
</tr>
<tr>
<td>Appendix D. Discrete Dynamical Systems — Maps</td>
<td></td>
</tr>
<tr>
<td>D.1 One-dimensional Maps</td>
<td>425</td>
</tr>
<tr>
<td>D.2 Two-dimensional Maps</td>
<td>433</td>
</tr>
<tr>
<td>D.3 Twist Maps and Torus Breakdown</td>
<td>437</td>
</tr>
<tr>
<td>Answers to Problems</td>
<td>445</td>
</tr>
<tr>
<td>Bibliography</td>
<td>463</td>
</tr>
<tr>
<td>Index</td>
<td>465</td>
</tr>
</tbody>
</table>

### Appendix A. Vectors

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1 Definitions and Elementary Properties</td>
<td>381</td>
</tr>
</tbody>
</table>
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 V ............................................ 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 $f/r^2$ ............................... 45
1.5.2 The One-Dimensional Dirac Delta Function ....... 46
## CONTENTS

### 6 Magnetic Fields in Matter

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

### 7 Electrodynamics

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 Electromotive Force</td>
<td>285</td>
</tr>
<tr>
<td>7.1.1 Ohm's Law</td>
<td>285</td>
</tr>
<tr>
<td>7.1.2 Electromotive Force</td>
<td>292</td>
</tr>
<tr>
<td>7.1.3 Motional enm</td>
<td>294</td>
</tr>
<tr>
<td>7.2 Electromagnetic Induction</td>
<td>301</td>
</tr>
<tr>
<td>7.2.1 Faraday's Law</td>
<td>301</td>
</tr>
<tr>
<td>7.2.2 The Induced Electric Field</td>
<td>305</td>
</tr>
<tr>
<td>7.2.3 Inductance</td>
<td>310</td>
</tr>
<tr>
<td>7.2.4 Energy in Magnetic Fields</td>
<td>317</td>
</tr>
<tr>
<td>7.3 Maxwell's Equations</td>
<td>321</td>
</tr>
<tr>
<td>7.3.1 Electrodynamics Before Maxwell</td>
<td>321</td>
</tr>
<tr>
<td>7.3.2 How Maxwell Fixed Ampère's Law</td>
<td>323</td>
</tr>
<tr>
<td>7.3.3 Maxwell's Equations</td>
<td>326</td>
</tr>
<tr>
<td>7.3.4 Magnetic Charge</td>
<td>327</td>
</tr>
<tr>
<td>7.3.5 Maxwell's Equations in Matter</td>
<td>328</td>
</tr>
<tr>
<td>7.3.6 Boundary Conditions</td>
<td>331</td>
</tr>
</tbody>
</table>

### 8 Conservation Laws

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Charge and Energy</td>
<td>345</td>
</tr>
<tr>
<td>8.1.1 The Continuity Equation</td>
<td>345</td>
</tr>
<tr>
<td>8.1.2 Poynting's Theorem</td>
<td>346</td>
</tr>
<tr>
<td>8.2 Momentum</td>
<td>349</td>
</tr>
<tr>
<td>8.2.1 Newton's Third Law in Electrodynamics</td>
<td>349</td>
</tr>
<tr>
<td>8.2.2 Maxwell's Stress Tensor</td>
<td>351</td>
</tr>
<tr>
<td>8.2.3 Conservation of Momentum</td>
<td>355</td>
</tr>
<tr>
<td>8.2.4 Angular Momentum</td>
<td>358</td>
</tr>
</tbody>
</table>

### 9 Electromagnetic Waves

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

### 10 Potentials and Fields

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1 The Potential Formulation</td>
<td>416</td>
</tr>
<tr>
<td>10.1.1 Scalar and Vector Potentials</td>
<td>416</td>
</tr>
<tr>
<td>10.1.2 Gauge Transformations</td>
<td>419</td>
</tr>
<tr>
<td>10.1.3 Coulomb Gauge and Lorentz Gauge</td>
<td>421</td>
</tr>
<tr>
<td>10.2 Continuous Distributions</td>
<td>422</td>
</tr>
<tr>
<td>10.2.1 Retarded Potentials</td>
<td>422</td>
</tr>
<tr>
<td>10.2.2 Jeffreymo's Equations</td>
<td>427</td>
</tr>
<tr>
<td>10.3 Point Charges</td>
<td>429</td>
</tr>
<tr>
<td>10.3.1 Liénard-Wiechert Potential</td>
<td>429</td>
</tr>
<tr>
<td>10.3.2 The Fields of a Moving Point Charge</td>
<td>435</td>
</tr>
</tbody>
</table>
# CONTENTS

## 11 Radiation

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

## Appendix

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
### Contents

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, 93  
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 Schrödinger 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-DEPENDENT 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 Hyperfine 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**
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.

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-Thomas 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
### 7 THE PERFECT CLASSICAL GAS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 The Definition of the Perfect Classical Gas</td>
<td>166</td>
</tr>
<tr>
<td>7.2 The Partition Function</td>
<td>169</td>
</tr>
<tr>
<td>7.3 Validity Criterion for the Classical Regime</td>
<td>175</td>
</tr>
<tr>
<td>7.4 The Equation of State</td>
<td>178</td>
</tr>
<tr>
<td>7.5 The Heat Capacity</td>
<td>179</td>
</tr>
<tr>
<td>7.6 The Entropy</td>
<td>181</td>
</tr>
<tr>
<td>7.7 The Maxwell Velocity Distribution</td>
<td>184</td>
</tr>
<tr>
<td>7.8 Real Gases</td>
<td>191</td>
</tr>
<tr>
<td>7.9 Classical Statistical Mechanics</td>
<td>204</td>
</tr>
<tr>
<td>7.9.1 The Equipartition of Energy</td>
<td>210</td>
</tr>
<tr>
<td>PROBLEMS 7</td>
<td>214</td>
</tr>
</tbody>
</table>

### 8 PHASE EQUILIBRIA

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Equilibrium Conditions</td>
<td>218</td>
</tr>
<tr>
<td>8.2 Alternative Derivation of the Equilibrium Conditions</td>
<td>221</td>
</tr>
<tr>
<td>8.3 Discussion of the Equilibrium Conditions</td>
<td>223</td>
</tr>
<tr>
<td>8.4 The Clausius–Clapeyron Equation</td>
<td>226</td>
</tr>
<tr>
<td>8.5 Applications of the Clausius–Clapeyron Equation</td>
<td>230</td>
</tr>
<tr>
<td>8.5.1 Pressure Dependence of the Melting Point</td>
<td>230</td>
</tr>
<tr>
<td>8.5.2 Pressure Dependence of the Boiling Point</td>
<td>231</td>
</tr>
<tr>
<td>8.5.3 The Vapour Pressure Curve</td>
<td>231</td>
</tr>
<tr>
<td>8.6 The Critical Point</td>
<td>232</td>
</tr>
<tr>
<td>PROBLEMS 8</td>
<td>237</td>
</tr>
</tbody>
</table>

### 9 THE PERFECT QUANTAL GAS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 Introductory Remarks</td>
<td>239</td>
</tr>
<tr>
<td>9.2 Quantum Statistics</td>
<td>240</td>
</tr>
<tr>
<td>9.3 The Partition Function</td>
<td>244</td>
</tr>
<tr>
<td>PROBLEMS 9</td>
<td>245</td>
</tr>
</tbody>
</table>

### 10 BLACK-BODY RADIATION

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1 Introductory Remarks</td>
<td>246</td>
</tr>
<tr>
<td>10.2 The Partition Function for Photons</td>
<td>247</td>
</tr>
<tr>
<td>10.3 Planck’s Law: Derivation</td>
<td>249</td>
</tr>
<tr>
<td>10.4 The Properties of Black-Body Radiation</td>
<td>251</td>
</tr>
<tr>
<td>10.5 The Thermodynamics of Black-Body Radiation</td>
<td>256</td>
</tr>
<tr>
<td>PROBLEMS 10</td>
<td>259</td>
</tr>
</tbody>
</table>

### 11 SYSTEMS WITH VARIABLE PARTICLE NUMBERS

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

### A MATHEMATICAL RESULTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1 Stirling’s Formula</td>
<td>317</td>
</tr>
<tr>
<td>A.2 Evaluation of (\int_0^\infty (e^{-x} - 1) dx)</td>
<td>318</td>
</tr>
<tr>
<td>A.3 Some Kinetic Theory Integrals</td>
<td>321</td>
</tr>
</tbody>
</table>

### B THE DENSITY OF STATES

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1 The General Case</td>
<td>324</td>
</tr>
<tr>
<td>B.2 The Schrödinger Equation</td>
<td>331</td>
</tr>
<tr>
<td>B.3 Electromagnetic Waves</td>
<td>332</td>
</tr>
<tr>
<td>B.4 Elastic Waves in a Continuous Solid</td>
<td>333</td>
</tr>
</tbody>
</table>

### C MAGNETIC SYSTEMS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>336</td>
</tr>
</tbody>
</table>

### D HINTS FOR SOLVING PROBLEMS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bibliography</td>
<td>340</td>
</tr>
<tr>
<td>Index</td>
<td>374</td>
</tr>
<tr>
<td>Physical constants and conversion factors</td>
<td>379</td>
</tr>
</tbody>
</table>

*BSections 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.*