

# Contents

Preface	vii
Preface to the second edition	x
<b>I Preliminaries</b>	<b>1</b>
<b>1 Introduction</b>	<b>2</b>
1.1 What is a mole?	3
1.2 The thermodynamic limit	4
1.3 The ideal gas	6
1.4 Combinatorial problems	7
1.5 Plan of the book	9
Exercises	12
<b>2 Heat</b>	<b>13</b>
2.1 A definition of heat	13
2.2 Heat capacity	14
Exercises	17
<b>3 Probability</b>	<b>18</b>
3.1 Discrete probability distributions	19
3.2 Continuous probability distributions	20
3.3 Linear transformation	21
3.4 Variance	22
3.5 Linear transformation and the variance	23
3.6 Independent variables	24
3.7 Binomial distribution	26
Further reading	29
Exercises	29
<b>4 Temperature and the Boltzmann factor</b>	<b>32</b>
4.1 Thermal equilibrium	32
4.2 Thermometers	33
4.3 The microstates and macrostates	35
4.4 A statistical definition of temperature	36
4.5 Ensembles	38
4.6 Canonical ensemble	38
4.7 Applications of the Boltzmann distribution	42
Further reading	46
Exercises	46

## II Kinetic theory of gases 47

<b>5</b>	<b>The Maxwell–Boltzmann distribution</b>	<b>48</b>
5.1	The velocity distribution	48
5.2	The speed distribution	49
5.3	Experimental justification	51
	Exercises	54
<b>6</b>	<b>Pressure</b>	<b>56</b>
6.1	Molecular distributions	57
6.2	The ideal gas law	58
6.3	Dalton's law	60
	Exercises	61
<b>7</b>	<b>Molecular effusion</b>	<b>64</b>
7.1	Flux	64
7.2	Effusion	66
	Exercises	69
<b>8</b>	<b>The mean free path and collisions</b>	<b>70</b>
8.1	The mean collision time	70
8.2	The collision cross-section	71
8.3	The mean free path	73
	Exercises	74

## III Transport and thermal diffusion 75

<b>9</b>	<b>Transport properties in gases</b>	<b>76</b>
9.1	Viscosity	76
9.2	Thermal conductivity	81
9.3	Diffusion	83
9.4	More detailed theory	86
	Further reading	88
	Exercises	89
<b>10</b>	<b>The thermal diffusion equation</b>	<b>90</b>
10.1	Derivation of the thermal diffusion equation	90
10.2	The one-dimensional thermal diffusion equation	91
10.3	The steady state	94
10.4	The thermal diffusion equation for a sphere	94
10.5	Newton's law of cooling	99
10.6	The Prandtl number	100
10.7	Sources of heat	101
10.8	Particle diffusion	102
	Exercises	103

<b>IV</b>	<b>The first law</b>	<b>107</b>
<b>11</b>	<b>Energy</b>	<b>108</b>
11.1	Some definitions	108
11.2	The first law of thermodynamics	110
11.3	Heat capacity	112
	Exercises	115
<b>12</b>	<b>Isothermal and adiabatic processes</b>	<b>118</b>
12.1	Reversibility	118
12.2	Isothermal expansion of an ideal gas	120
12.3	Adiabatic expansion of an ideal gas	121
12.4	Adiabatic atmosphere	121
	Exercises	123
<b>V</b>	<b>The second law</b>	<b>125</b>
<b>13</b>	<b>Heat engines and the second law</b>	<b>126</b>
13.1	The second law of thermodynamics	126
13.2	The Carnot engine	127
13.3	Carnot's theorem	130
13.4	Equivalence of Clausius' and Kelvin's statements	131
13.5	Examples of heat engines	131
13.6	Heat engines running backwards	133
13.7	Clausius' theorem	134
	Further reading	137
	Exercises	137
<b>14</b>	<b>Entropy</b>	<b>140</b>
14.1	Definition of entropy	140
14.2	Irreversible change	140
14.3	The first law revisited	142
14.4	The Joule expansion	144
14.5	The statistical basis for entropy	146
14.6	The entropy of mixing	147
14.7	Maxwell's demon	149
14.8	Entropy and probability	150
	Exercises	153
<b>15</b>	<b>Information theory</b>	<b>157</b>
15.1	Information and Shannon entropy	157
15.2	Information and thermodynamics	159
15.3	Data compression	160
15.4	Quantum information	162
15.5	Conditional and joint probabilities	165
15.6	Bayes' theorem	165
	Further reading	168
	Exercises	169

## VI Thermodynamics in action 171

<b>16 Thermodynamic potentials</b>	<b>172</b>
16.1 Internal energy, $U$	172
16.2 Enthalpy, $H$	173
16.3 Helmholtz function, $F$	174
16.4 Gibbs function, $G$	175
16.5 Constraints	176
16.6 Maxwell's relations	179
Exercises	187
<b>17 Rods, bubbles, and magnets</b>	<b>191</b>
17.1 Elastic rod	191
17.2 Surface tension	194
17.3 Electric and magnetic dipoles	195
17.4 Paramagnetism	196
Exercises	201
<b>18 The third law</b>	<b>203</b>
18.1 Different statements of the third law	203
18.2 Consequences of the third law	205
Exercises	208

## VII Statistical mechanics 209

<b>19 Equipartition of energy</b>	<b>210</b>
19.1 Equipartition theorem	210
19.2 Applications	213
19.3 Assumptions made	215
19.4 Brownian motion	217
Exercises	218
<b>20 The partition function</b>	<b>219</b>
20.1 Writing down the partition function	220
20.2 Obtaining the functions of state	221
20.3 The big idea	228
20.4 Combining partition functions	228
Exercises	232
<b>21 Statistical mechanics of an ideal gas</b>	<b>233</b>
21.1 Density of states	233
21.2 Quantum concentration	235
21.3 Distinguishability	236
21.4 Functions of state of the ideal gas	237
21.5 Gibbs paradox	240
21.6 Heat capacity of a diatomic gas	241
Exercises	243

<b>22 The chemical potential</b>	<b>244</b>
22.1 A definition of the chemical potential	244
22.2 The meaning of the chemical potential	245
22.3 Grand partition function	247
22.4 Grand potential	248
22.5 Chemical potential as Gibbs function per particle	250
22.6 Many types of particle	250
22.7 Particle number conservation laws	251
22.8 Chemical potential and chemical reactions	252
22.9 Osmosis	257
Further reading	261
Exercises	262
<b>23 Photons</b>	<b>263</b>
23.1 The classical thermodynamics of electromagnetic radiation	264
23.2 Spectral energy density	265
23.3 Kirchhoff's law	266
23.4 Radiation pressure	268
23.5 The statistical mechanics of the photon gas	269
23.6 Black-body distribution	270
23.7 Cosmic microwave background radiation	273
23.8 The Einstein A and B coefficients	274
Further reading	277
Exercises	278
<b>24 Phonons</b>	<b>279</b>
24.1 The Einstein model	279
24.2 The Debye model	281
24.3 Phonon dispersion	284
Further reading	287
Exercises	287
<b>VIII Beyond the ideal gas</b>	<b>289</b>
<b>25 Relativistic gases</b>	<b>290</b>
25.1 Relativistic dispersion relation for massive particles	290
25.2 The ultrarelativistic gas	290
25.3 Adiabatic expansion of an ultrarelativistic gas	293
Exercises	295
<b>26 Real gases</b>	<b>296</b>
26.1 The van der Waals gas	296
26.2 The Dieterici equation	304
26.3 Virial expansion	306
26.4 The law of corresponding states	310
Exercises	312

<b>27</b>	<b>Cooling real gases</b>	<b>313</b>
27.1	The Joule expansion	313
27.2	Isothermal expansion	315
27.3	Joule–Kelvin expansion	316
27.4	Liquefaction of gases	318
	Exercises	320
<b>28</b>	<b>Phase transitions</b>	<b>321</b>
28.1	Latent heat	321
28.2	Chemical potential and phase changes	324
28.3	The Clausius–Clapeyron equation	324
28.4	Stability and metastability	329
28.5	The Gibbs phase rule	332
28.6	Colligative properties	334
28.7	Classification of phase transitions	335
28.8	The Ising model	338
	Further reading	343
	Exercises	343
<b>29</b>	<b>Bose–Einstein and Fermi–Dirac distributions</b>	<b>345</b>
29.1	Exchange and symmetry	345
29.2	Wave functions of identical particles	346
29.3	The statistics of identical particles	349
	Further reading	353
	Exercises	354
<b>30</b>	<b>Quantum gases and condensates</b>	<b>358</b>
30.1	The non-interacting quantum fluid	358
30.2	The Fermi gas	361
30.3	The Bose gas	366
30.4	Bose–Einstein condensation (BEC)	367
	Further reading	373
	Exercises	373
<b>IX</b>	<b>Special topics</b>	<b>375</b>
<b>31</b>	<b>Sound waves</b>	<b>376</b>
31.1	Sound waves under isothermal conditions	377
31.2	Sound waves under adiabatic conditions	377
31.3	Are sound waves in general adiabatic or isothermal?	378
31.4	Derivation of the speed of sound within fluids	379
	Further reading	382
	Exercises	382
<b>32</b>	<b>Shock waves</b>	<b>383</b>
32.1	The Mach number	383
32.2	Structure of shock waves	383
32.3	Shock conservation laws	385

32.4	The Rankine–Hugoniot conditions	386
	Further reading	389
	Exercises	389
<b>33</b>	<b>Brownian motion and fluctuations</b>	<b>390</b>
33.1	Brownian motion	390
33.2	Johnson noise	393
33.3	Fluctuations	394
33.4	Fluctuations and the availability	395
33.5	Linear response	397
33.6	Correlation functions	400
	Further reading	407
	Exercises	407
<b>34</b>	<b>Non-equilibrium thermodynamics</b>	<b>408</b>
34.1	Entropy production	408
34.2	The kinetic coefficients	409
34.3	Proof of the Onsager reciprocal relations	410
34.4	Thermoelectricity	413
34.5	Time reversal and the arrow of time	417
	Further reading	419
	Exercises	419
<b>35</b>	<b>Stars</b>	<b>420</b>
35.1	Gravitational interaction	421
35.2	Nuclear reactions	426
35.3	Heat transfer	427
	Further reading	434
	Exercises	434
<b>36</b>	<b>Compact objects</b>	<b>435</b>
36.1	Electron degeneracy pressure	435
36.2	White dwarfs	437
36.3	Neutron stars	438
36.4	Black holes	440
36.5	Accretion	441
36.6	Black holes and entropy	442
36.7	Life, the Universe, and entropy	443
	Further reading	445
	Exercises	445
<b>37</b>	<b>Earth's atmosphere</b>	<b>446</b>
37.1	Solar energy	446
37.2	The temperature profile in the atmosphere	447
37.3	Radiative transfer	449
37.4	The greenhouse effect	452
37.5	Global warming	456
	Further reading	460
	Exercises	460

<b>A Fundamental constants</b>	<b>461</b>
<b>B Useful formulae</b>	<b>462</b>
<b>C Useful mathematics</b>	<b>464</b>
C.1 The factorial integral	464
C.2 The Gaussian integral	464
C.3 Stirling's formula	467
C.4 Riemann zeta function	469
C.5 The polylogarithm	470
C.6 Partial derivatives	471
C.7 Exact differentials	472
C.8 Volume of a hypersphere	473
C.9 Jacobians	473
C.10 The Dirac delta function	475
C.11 Fourier transforms	475
C.12 Solution of the diffusion equation	476
C.13 Lagrange multipliers	477
<b>D The electromagnetic spectrum</b>	<b>479</b>
<b>E Some thermodynamical definitions</b>	<b>480</b>
<b>F Thermodynamic expansion formulae</b>	<b>481</b>
<b>G Reduced mass</b>	<b>482</b>
<b>H Glossary of main symbols</b>	<b>483</b>
<b>Bibliography</b>	<b>485</b>
<b>Index</b>	<b>489</b>