

# Contents

## Preface

	xv
1 Basic thermodynamic and biochemical concepts	1
Fundamental thermodynamic concepts	2
States of matter	2
Pressure	2
Temperature	5
Volume, mass, and number	6
Properties of gases	6
The ideal gas laws	6
Gas mixtures	8
Kinetic energy of gases	9
Real gases	9
Derivation box 1.1 Relationship between the average velocity and pressure	10
Liquifying gases for low-temperature spectroscopy	12
Molecular basis for life	13
Cell membranes	14
Amino acids	15
Classification of amino acids by their side chains	15
DNA and RNA	18
Problems	20
<b>Part 1: Thermodynamics and kinetics</b>	<b>21</b>
2 First law of thermodynamics	23
Systems	23
State functions	25
First law of thermodynamics	26
Research direction: drug design I	27
Work	29
Specific heat	31
Internal energy for an ideal gas	31
Enthalpy	33

Dependence of specific heat on internal energy and enthalpy	34
Derivation box 2.1 State functions described using partial derivatives	34
Enthalpy changes of biochemical reactions	38
Research direction: global climate change	40
References	44
Problems	45
<b>3 Second law of thermodynamics</b>	<b>46</b>
Entropy	47
Entropy changes for reversible and irreversible processes	49
The second law of thermodynamics	51
Interpretation of entropy	52
Third law of thermodynamics	53
Gibbs energy	54
Relationship between the Gibbs energy and the equilibrium constant	55
Research direction: drug design II	56
Gibbs energy for an ideal gas	58
Using the Gibbs energy	59
Carnot cycle and hybrid cars	60
Derivation box 3.1 Entropy as a state function	63
Research direction: nitrogen fixation	66
References	69
Problems	69
<b>4 Phase diagrams, mixtures, and chemical potential</b>	<b>71</b>
Substances may exist in different phases	71
Phase diagrams and transitions	72
Chemical potential	73
Properties of lipids described using the chemical potential	74
Lipid and detergent formation into micelles and bilayers	75
Research direction: lipid rafts	77
Determination of micelle formation using surface tension	79
Mixtures	82
Raoult's law	85
Osmosis	88
Research direction: protein crystallization	88
References	92
Problems	92
<b>5 Equilibria and reactions involving protons</b>	<b>94</b>
Gibbs energy minimum	94
Derivation box 5.1 Relationship between the Gibbs energy and equilibrium constant	95
Response of the equilibrium constant to condition changes	98
Acid–base equilibria	99
Protonation states of amino acid residues	105

Buffers	106
Buffering in the cardiovascular system	108
Research direction: proton-coupled electron transfer and pathways	108
References	111
Problems	112
6 Oxidation/reduction reactions and bioenergetics	114
Oxidation/reduction reactions	114
Electrochemical cells	115
The Nernst equation	116
Midpoint potentials	117
Gibbs energy of formation and activity	120
Ionic strength	122
Adenosine triphosphate	123
Chemiosmotic hypothesis	124
Research direction: respiratory chain	126
Research direction: ATP synthase	128
References	131
Problems	132
7 Kinetics and enzymes	134
The rate of a chemical reaction	134
Parallel first-order reactions	137
Sequential first-order reactions	139
Second-order reactions	140
The order of a reaction	141
Reactions that approach equilibrium	142
Activation energy	143
Research direction: electron transfer I: energetics	144
Derivation box 7.1 Derivation of the Marcus relationship	146
Enzymes	147
Enzymes lower the activation energy	148
Enzyme mechanisms	150
Research direction: dynamics in enzyme mechanism	150
Michaelis–Menten mechanism	151
Lineweaver–Burk equation	155
Enzyme activity	155
Research direction: the RNA world	158
References	160
Problems	161
8 The Boltzmann distribution and statistical thermodynamics	163
Probability	163
Boltzmann distribution	165
Partition function	166

Statistical thermodynamics	167
Research direction: protein folding and prions	168
Prions	169
References	171
Problems	171
<b>Part 2: Quantum mechanics and spectroscopy 173</b>	
9 Quantum theory: introduction and principles	175
Classical concepts	175
Experimental failures of classical physics	177
Blackbody radiation	177
Photoelectric effect	180
Atomic spectra	180
Principles of quantum theory	182
Wave-particle duality	182
Schrödinger's equation	184
Born interpretation	188
General approach for solving Schrödinger's equation	190
Interpretation of quantum mechanics	191
Heisenberg Uncertainty Principle	192
A quantum-mechanical world	193
Research direction: Schrödinger's cat	194
References	195
Problems	196
10 Particle in a box and tunneling	198
One-dimensional particle in a box	198
Properties of the solutions	200
Energy and wavefunction	200
Symmetry	201
Wavelength	202
Probability	202
Orthogonality	203
Average or expectation value	203
Transitions	204
Research direction: carotenoids	205
Two-dimensional particle in a box	207
Tunneling	209
Research direction: probing biological membranes	211
Research direction: electron transfer II: distance dependence	215
References	218
Problems	218

11	Vibrational motion and infrared spectroscopy	221
	Simple harmonic oscillator: classical theory	221
	Potential energy for the simple harmonic oscillator	223
	Simple harmonic oscillator: quantum theory	223
	Derivation box 11.1 Solving Schrödinger's equation for the simple harmonic oscillator	224
	Properties of the solutions	225
	Forbidden region	228
	Transitions	229
	Vibrational spectra	230
	Research direction: hydrogenase	232
	References	235
	Problems	235
12	Atomic structure: hydrogen atom and multi-electron atoms	238
	Schrödinger's equation for the hydrogen atom	238
	Derivation box 12.1 Solving Schrödinger's equation for the hydrogen atom	239
	Separation of variables	239
	Angular solution	240
	Radial solution	243
	Properties of the general solution	244
	Angular momentum	246
	Orbitals	247
	s Orbitals	247
	p Orbitals	251
	d Orbitals	252
	Transitions	253
	Research direction: hydrogen economy	254
	Spin	257
	Derivation box 12.2 Relativistic equations	258
	Multi-electron atoms	260
	Empirical constants	260
	Self-consistent field theory (Hartree–Fock)	261
	Helium atom	262
	Spin–orbital coupling	264
	Periodic table	265
	References	267
	Problems	267
13	Chemical bonds and protein interactions	270
	Schrödinger's equation for a hydrogen molecule	270
	Valence bonds	275
	The Hückel model	276
	Interactions in proteins	276

Peptide bonds	278
Steric effects	278
Hydrogen bonds	279
Electrostatic interactions	280
Hydrophobic effects	280
Secondary structure	282
Determination of secondary structure using circular dichroism	284
Research direction: modeling protein structures and folding	284
References	289
Problems	289
<b>14 Electronic transitions and optical spectroscopy</b>	<b>291</b>
The nature of light	291
The Beer–Lambert law	293
Measuring absorption	294
Transitions	296
Derivation box 14.1 Relationship between the Einstein coefficient and electronic states	298
Lasers	300
Selection rules	301
The Franck–Condon principle	302
The relationship between emission and absorption spectra	303
The yield of fluorescence	305
Fluorescence resonance energy transfer	306
Measuring fluorescence	306
Phosphorescence	307
Research direction: probing energy transfer using two-dimensional optical spectroscopy	307
Research direction: single-molecule spectroscopy	310
Holliday junctions	312
References	315
Problems	315
<b>15 X-ray diffraction and extended X-ray absorption fine structure</b>	<b>317</b>
Bragg's law	319
Bravais lattices	320
Protein crystals	322
Diffraction from crystals	323
Derivation box 15.1 Phases of complex numbers	325
Phase determination	328
Molecular replacement	328
Isomorphous replacement	329
Anomalous dispersion	329
Model building	331
Experimental measurement of X-ray diffraction	332

Examples of protein structures	335
Research direction: nitrogenase	336
Extended X-ray absorption fine structure	339
References	342
Problems	342
<b>16 Magnetic resonance</b>	<b>344</b>
NMR	344
Chemical shifts	347
Spin-spin interactions	348
Pulse techniques	349
Two-dimensional NMR: nuclear Overhauser effect	351
NMR spectra of amino acids	352
Research direction: development of new NMR techniques	352
Determination of macromolecular structures	357
Research direction: spinal muscular atrophy	357
MRI	360
Electron spin resonance	362
Hyperfine structure	365
Electron nuclear double resonance	365
Spin probes	366
Research direction: heme proteins	367
Research direction: ribonucleotide reductase	369
References and further reading	370
Problems	371
<b>Part 3: Understanding biological systems using physical chemistry</b>	<b>373</b>
<b>17 Signal transduction</b>	<b>375</b>
Biochemical pathway for visual response	375
Spectroscopic studies of rhodopsin	377
Bacteriorhodopsin	378
Structural studies	380
Comparison of rhodopsins from different organisms	384
Rhodopsin proteins in visual response	387
References and further reading	387
Problems	388
<b>18 Membrane potentials, transporters, and channels</b>	<b>390</b>
Membrane potentials	390
Energetics of transport across membranes	391
Transporters	394
Ion channels	397
References and further reading	402
Problems	403

19	Molecular imaging	405
	Imaging in cells and bodies	405
	Green fluorescent protein	405
	Mechanism of chromophore formation	408
	Fluorescence resonance energy transfer	410
	Imaging of GFP in cells	412
	Imaging in organisms	414
	Radioactive decay	415
	PET	416
	Parkinson's disease	418
	References and further reading	419
	Problems	419
20	Photosynthesis	421
	Energy transfer and light-harvesting complexes	423
	Electron transfer, bacterial reaction centers, and photosystem I	425
	Water oxidation	430
	References and further reading	436
	Problems	437
	Answers to problems	439
	Index	488
	Fundamental constants	493
	Conversion factors for energy units	493
	The periodic table	494