

Table of Contents

Introduction v

Chapter 1 Building Blocks and Structure 1

- 1.1 Atoms and Ions 1
 - 1.1.1 Subatomic Particles 1
 - 1.1.2 Atomic Constituents of Life 3
 - 1.1.3 Ions 3
- 1.2 Molecules Essential for Life 4
 - 1.2.1 Water 4
 - 1.2.2 Proteins 5
 - 1.2.3 Lipids 8
 - 1.2.4 Carbohydrates 10
 - 1.2.5 Cholesterol 10
 - 1.2.6 Nucleic Acid 11
- 1.3 What Is Life? 11
 - 1.3.1 Requirements for Life 12
 - 1.3.2 Domains of Life 12
 - 1.3.3 Characteristics of Living Cells 12
 - 1.3.4 Structure of Living Cells 13
 - 1.3.5 Boundary of Life 13

Chapter 2 Living State Interactions 17

- 2.1 Forces and Molecular Bonds 17
 - 2.1.1 Ionic Bonds 18
 - 2.1.2 Covalent Bonds 19
 - 2.1.3 Hydrogen Bonds 19
 - 2.1.4 Van der Waal Forces 20
- 2.2 Electric and Thermal Interactions 20
- 2.3 Electric Dipoles 21
 - 2.3.1 Polarization and Induced Dipoles 23

2.4	Casimir Interactions	24
2.5	Domains of Physics in Biology	26
	Exercises	27
Chapter 3	Heat Transfer in Biomaterials	29
3.1	Heat Transfer Mechanisms	29
3.1.1	Conduction	30
3.1.2	Convection	30
3.1.3	Radiation	31
3.2	The Heat Equation	32
3.2.1	Transient Heat Flow	32
3.2.2	Steady State Heat Flow	34
3.3	Joule Heating of Tissue	35
	Exercises	37
Chapter 4	Living State Thermodynamics	39
4.1	Thermodynamic Equilibrium	40
4.2	First Law of Thermodynamics and Conservation of Energy	40
4.3	Entropy and the Second Law of Thermodynamics	41
4.3.1	Does Life Violate the Second Law?	41
4.3.2	Measures of Entropy?	42
4.3.3	Free Expansion of a Gas	42
4.4	Physics of Many Particle Systems	43
4.4.1	How Boltzmann Factors in Biology	44
4.4.2	Canonical Partition Function	45
4.4.3	Average Energy	46
4.4.4	Entropy and Free Energy	47
4.4.5	Heat Capacity	48
4.5	Two-State Systems	49
4.6	Continuous Energy Distribution	50
4.7	Composite Systems	50
4.7.1	DNA Stretching	51
4.8	Casimir Contribution to the Free Energy	53
4.8.1	Lipid Bilayer Tubes	53
4.8.2	Rouleaux	53
4.9	Protein Folding and Unfolding	55
4.9.1	Protein Unfolding	55
4.9.2	Levinthal's Paradox	55
4.9.3	Energy Landscape	56

	4.9.4	Folding on a Lattice	57
	4.9.5	Monte Carlo Methods	58
	4.9.6	Folding@home	59
	Exercises		59
Chapter 5	Open Systems and Chemical Thermodynamics		61
	5.1	Enthalpy, Gibbs Free Energy, and Chemical Potential	61
	5.2	Chemical Reactions	64
	5.2.1	First-Order Reactions	64
	5.2.2	Second-Order Reactions	65
	5.3	Activation Energy and Rate Constants	66
	5.3.1	Detailed Balance	68
	5.3.2	Nitrogen Fixation	69
	5.4	Enzymatic Reactions	70
	5.5	ATP Hydrolysis and Synthesis	73
	5.6	Entropy of Mixing	74
	5.7	The Grand Canonical Ensemble	74
	5.8	Hemoglobin	76
	Exercises		77
Chapter 6	Diffusion and Transport		79
	6.1	Maxwell-Boltzmann Statistics	79
	6.2	Brownian Motion	81
	6.3	Fick's Laws of Diffusion	84
	6.3.1	Fick's First Law	84
	6.3.2	Fick's Second Law	85
	6.3.3	Quantum Diffusion	86
	6.3.4	Time-Independent Concentrations	86
	6.3.5	Fick's Law for Growing Bacterial Cultures	87
	6.4	Sedimentation of Cell Cultures	88
	6.5	Diffusion in a Centrifuge	89
	6.6	Diffusion in an Electric Field	91
	6.7	Lateral Diffusion in Membranes	92
	6.8	Navier-Stokes Equation	93
	6.8.1	Reynolds Number	94
	6.9	Low Reynolds Number Transport	95
	6.9.1	Purcell's "Life at Low Reynolds Number"	95
	6.9.2	Coasting Distance of a Bacterium	95
	6.10	Active and Passive Membrane Transport	97
	Exercises		98

Chapter 7	Fluids	101
7.1	Laminar and Turbulent Fluid Flow	101
7.2	Bernoulli's Equation	102
7.3	Equation of Continuity	103
7.4	Venturi Effect	104
7.5	Fluid Dynamics of Circulatory Systems	106
7.5.1	Viscous Flow	106
7.5.2	Vessel Constriction and Aneurysm	107
7.5.3	Variation of Blood Pressure with Depth	108
7.5.4	Microgravity Effects	108
7.6	Capillary Action	109
	Exercises	110
Chapter 8	Bioenergetics and Molecular Motors	111
8.1	Kinesins, Dyneins, and Microtubule Dynamics	111
8.2	Brownian Motors	113
8.2.1	Feynman Ratchet	113
8.2.2	Kinesin Brownian Dynamics	115
8.2.3	Myosin Brownian Dynamics	115
8.3	ATP Synthesis in Mitochondria	116
8.3.1	Electron Transport Chain	116
8.3.2	ATP Synthase	117
8.3.3	Torque Generation in ATP Synthase	118
8.4	Photosynthesis in Chloroplasts	118
8.4.1	Photosystem II	120
8.4.2	Photosystem I	120
8.5	Light Absorption in Biomolecules	120
8.6	Vibrational Spectra of Biomolecules	122
8.6.1	Square Well Potential	122
8.6.2	Harmonic Oscillator Potential	122
	Exercises	125
Chapter 9	Passive Electrical Properties of Living Cells	127
9.1	Poisson-Boltzmann Equation	127
9.1.1	One-One Valent Electrolytes	129
9.1.2	Low Field Limit	130
9.1.3	Spherical Solution	130
9.2	Intrinsic Membrane Potentials	131
9.3	Induced Membrane Potentials	132
9.3.1	Plasma Membrane	132

Chapter 9	9.3.2	Liposome in a Static Electric Field	134
	9.3.3	Spherical Cell in an Alternating Electric Field	135
	9.3.4	Inertial Effects in Field-Induced Counterion Motion	136
	9.3.5	Induced Potentials in Organelle Membranes	136
	9.3.6	Mitochondrion in an Alternating Electric Field	137
9.4		Bioimpedance	138
	9.4.1	Time Harmonic Current Flow	138
	9.4.2	Dielectric Spectroscopy	139
	9.4.3	Debye Relaxation Model	142
	9.4.4	Cole Equation	142
	9.4.5	Maxwell-Wagner Effect	143
	9.4.6	Skin Impedance	144
	9.4.7	Electrode Polarization	144
9.5		Bioimpedance Simulator	145
9.6		Nonlinear Effects	148
		Exercises	149
Chapter 10	Nerve Conduction	153	
10.1		Nerve Impulses	153
10.2		Neurotransmitters and Synapses	154
10.3		Passive Transport in Dendrites	155
10.4		Active Transport and the Hodgkin-Huxley Equations	156
10.5		Simulation of Action Potential	160
	10.5.1	Excitation Threshold	160
	10.5.2	Neuronal Refractoriness	160
	10.5.3	Repetitive Spiking	161
10.6		FitzHugh-Nagumo Model	163
10.7		Action Potentials in the Earthworm Nerve Fiber	166
		Exercises	168
Chapter 11	Mechanical Properties of Biomaterials	169	
11.1		Elastic Moduli	169
	11.1.1	Young's Modulus	169
	11.1.2	Shear Modulus	170
	11.1.3	Poisson's Ratio	171
11.2		Electric Stresses in Biological Membranes	172
11.3		Mechanical Effects of Microgravity During Spaceflight	172
		Exercises	173

Chapter 12 Biomagnetism 177

- 12.1 Biomagnetic Field Sources 177
 - 12.1.1 Current Dipole Model 179
 - 12.1.2 Vector Potential Formulation 180
- 12.2 Nerve Impulses 180
- 12.3 Magnetotactic Bacteria 181
- 12.4 SQUID Magnetometry 182
 - 12.4.1 Josephson Effect 184
 - 12.4.2 Flux-Locked Loop 186
 - 12.4.3 Intrinsic Noise Factors 187
 - 12.4.4 Extrinsic Noise Factors 187
 - 12.4.5 Digital Filters 189
- 12.5 Magnetocardiography 189
- 12.6 Fetal Magnetocardiography 190
- 12.7 Magnetoencephalography 191
- Exercises 193

Chapter 13 Nonlinearity and Chaos in Biological Systems 195

- 13.1 Chaotic Dynamics 195
 - 13.1.1 Characteristics of Chaotic Dynamics 196
 - 13.1.2 Sensitive Dependence on Initial Conditions 197
 - 13.1.3 Phase Space 197
 - 13.1.4 Phase Space Reconstruction 198
 - 13.1.5 Poincaré Sections 199
 - 13.1.6 Lyapunov Exponents 200
 - 13.1.7 Power Spectra 200
- 13.2 Population Growth in a Limited Environment 202
- 13.3 Predator-Prey Models of Population Dynamics 203
- 13.4 Discrete Logistic Equation 204
 - 13.4.1 Period-Doubling Route to Chaos 206
 - 13.4.2 Bifurcation Diagrams 210
 - 13.4.3 Lyapunov Exponent of the Logistic Equation 212
 - 13.4.4 Shannon Entropy 213
- 13.5 Chaos in the Heart 215
- 13.6 Reaction Diffusion Equations 216
 - 13.6.1 Action Potentials 216
 - 13.6.2 Fertilization Calcium Waves 216
 - 13.6.3 Pattern Formation 217
- 13.7 Dynamics of the Driven Hodgkin-Huxley System 217
- 13.8 Models of DNA Motility 218
- Exercises 221

Chapter 14	Fractals and Complexity in the Life Sciences	225
14.1	Fractal Geometry	225
14.1.1	Computing Fractal Dimension	228
14.2	Fractal Structures in Biology	231
14.2.1	Fractal Ferns	231
14.2.2	Diffusion-Limited Aggregation	233
14.3	Power Laws in Biology	233
14.4	Self-Organized Criticality	235
14.4.1	BTW Sandpile Model	236
14.5	Extinction in the Bak–Sneppen Model	238
14.6	Power Law Behavior in Chemical Reactions	239
14.7	The Game of Life	241
14.7.1	SOC in the Game of Life	244
	Exercises	245
Chapter 15	Life and the Universe	247
15.1	Astrobiology	247
15.2	Extremophiles	248
15.3	Primordial Soup, Interstellar Gas, and Dust	249
15.3.1	The Miller Experiment	249
15.3.2	Chemistry of the Interstellar Medium	250
15.4	Searches for Life in the Solar System	251
15.4.1	Mars	251
15.4.2	Europa	256
15.4.3	Lake Vostok	257
15.5	Search for Life Outside the Solar System	258
15.5.1	Extrasolar Planets	258
15.5.2	SETI Initiatives	258
15.5.3	Anticoded Signals	259
15.5.4	Frequency Domain Searches	259
15.5.5	Radio Interferometry	260
15.5.6	The Drake Equation	261
15.6	Implications for Life in the Multiverse Picture	263
15.6.1	The Multiverse	263
15.6.2	The Anthropic Principle	264
15.6.3	Multiverse Cosmological Models	265
	Exercises	269

Appendix 1: Mathematical Formulas	273
Appendix 2: Overview of MATLAB®	281
Appendix 3: Derivation of the Heat Equation	289
Appendix 4: Derivation of Shannon's Entropy Formula	291
Exercises	294
Appendix 5: Thermodynamic Identities	295
Appendix 6: Kramers–Kronig Transformations	297
Appendix 7: Solution to the One-Dimensional Schrödinger Equation	299
Exercises	302
Appendix 8: Biophysical Applications of QuickField™	303
Appendix 9: Biological Material Properties	309
Appendix 10: Solutions of the Linearized Poisson–Boltzmann Equation	313
Exercises	323
References and Further Reading	325
Index	339