

Preface

1. On the Nature of Cells

1.1 Introduction: What Is a Cell?	1
1.2 The Basic Unit of Life	4
1.3 The Chemical Composition of Cells	6
1.4 A Sense of Cellular Scale	7
1.5 The Energetics of Cells	9
1.6 Are There Limits to the Mechanistic View?	10
1.7 The Mechanistic Viewpoint and God	11
1.8 What Is Cell Biology?	12
1.9 Summary	12
1.10 Questions	14

2. Plasma Membrane

2.1 The Cell Boundary	15
2.2 Topology of the Cell	15
2.3 Evidence for the Existence of a Plasma Membrane	16
2.4 Structure of the Plasma Membrane	20
2.5 Isolation of the Plasma Membrane	23
2.6 Chemical Composition of the Plasma Membrane	25
2.7 Transport Physiology	31
2.8 Electrical Properties of the Plasma Membrane	39
2.9 Characterization of Two Transport Proteins of the Plasma Membrane	41
2.9.1 Proton-Pumping ATPase	41
2.9.2 The K ⁺ Channel	44
2.10 Plasma Membrane-Localized Physiological Responses	47
2.10.1 Guard Cells	47
2.10.2 Motor Organs	48
2.10.3 Action Potentials	48
2.10.4 Cell Polarization	48
2.11 Structural Specializations of the Plasma Membrane	48

xiii

2.12 The Cytoskeleton-Plasma Membrane-Extracellular Matrix Continuum	49
2.13 Summary	50
2.14 Questions	50

3. Plasmodesmata

3.1 The Relationship between Cells and the Organism	51
3.2 Discovery and Occurrence of Plasmodesmata	52
3.3 Structure of Plasmodesmata	53
3.4 Isolation and Composition of Plasmodesmata	55
3.5 Permeability of Plasmodesmata	56
3.6 Summary	60
3.7 Questions	60

4. Endoplasmic Reticulum

4.1 Significance and Evolution of the Endoplasmic Reticulum	61
4.2 Discovery of the Endoplasmic Reticulum	61
4.3 Structure of the Endoplasmic Reticulum	62
4.4 Structural Specializations That Relate to Function	64
4.5 Isolation of RER and SER	65
4.6 Composition of the ER	65
4.7 Function of the Endoplasmic Reticulum	65
4.7.1 Lipid Synthesis	65
4.7.2 Protein Synthesis on the Endoplasmic Reticulum	66
4.7.3 Protein Glycosylation (Carbohydrate Synthesis)	71
4.7.4 Calcium Regulation	71
4.7.5 Phenylpropanoid and Flavonoid Synthesis	73
4.8 Summary	74
4.9 Questions	74

5. Peroxisomes

5.1	Discovery of Microbodies	75
5.2	Isolation of Peroxisomes	75
5.3	Composition of Peroxisomes	76
5.4	Function of Peroxisomes	76
5.4.1	β -Oxidation	76
5.4.2	Photorespiration	78
5.5	Relationship between Glyoxysomes and Peroxisomes	81
5.6	Metabolite Channeling	83
5.7	Other Functions	85
5.8	Biogenesis of Peroxisomes	86
5.9	Evolution of Peroxisomes	88
5.10	Summary	88
5.11	Questions	88

6. Golgi Apparatus

6.1	Discovery and Structure of the Golgi Apparatus	89
6.2	Polarity of the Golgi Stack	91
6.3	Isolation of the Golgi Apparatus	92
6.4	Composition of the Golgi Apparatus	93
6.5	Function of the Golgi Apparatus	93
6.5.1	Processing of Glycoproteins	93
6.5.2	Synthesis of Carbohydrates	93
6.5.3	Transport of Sugars	94
6.6	The Mechanism of Movement from Cisterna to Cisterna	94
6.7	Positioning of the Golgi Apparatus	98
6.8	Summary	99
6.9	Questions	99

7. The Vacuole

7.1	Discovery of the Vacuole	101
7.2	Structure, Biogenesis, and Dynamic Aspects of Vacuoles	102
7.3	Isolation of Vacuoles	105
7.4	Composition of Vacuoles	106
7.5	Transport across the Vacuolar Membrane	108
7.5.1	Proton-Translocating Pumps	109
7.5.2	ABC (ATP-Binding Cassette) Transporters or Traffic ATPases	110
7.5.3	Slowly Activated Vacuolar Channels	110
7.5.4	Water Channels	111
7.6	Functions of the Vacuole	111
7.6.1	Proteolysis and Recycling	111
7.6.2	Taking up Space	112
7.6.3	Storage and Homeostasis	113
7.6.4	Role in Turgor Generation	115
7.6.5	Other Functions	117
7.7	Biotechnology	117
7.8	Summary	117
7.9	Questions	118

8. Movement within the Endomembrane System

8.1	Discovery of the Secretory Pathway	119
8.2	Movement to the Plasma Membrane and the Extracellular Matrix	123
8.2.1	Movement between the ER and the Golgi Apparatus	124
8.2.2	Movement from the Golgi Apparatus to the Plasma Membrane	125
8.3	Movement from the ER to the Golgi Apparatus to the Vacuole	126
8.4	Movement from the ER to the Vacuole	126
8.5	Movement from the Plasma Membrane to the Endomembranes	127
8.5.1	Fluid-Phase Endocytosis	127
8.5.2	Receptor-Mediated Endocytosis	130
8.5.3	Piggyback Endocytosis	131
8.6	Disruption of Intracellular Secretory and Endocytotic Pathways	131
8.7	Summary	132
8.8	Questions	132

9. Cytoplasmic Structure

9.1	Historical Survey of the Study of Cytoplasmic Structure	133
9.2	Chemical Composition of Protoplasm	136
9.3	Physical Properties of Cytoplasm	137
9.3.1	Viscosity of the Cytoplasm	138
9.3.2	Elasticity of the Cytoplasm	147
9.4	Microtrabecular Lattice	148
9.4.1	Function of the Microtrabecular Lattice in Polarity	148
9.5	Summary	149
9.6	Questions	149

10. Actin and Microfilament-Mediated Processes

10.1	Discovery of Actomyosin and the Mechanism of Muscle Movement	151
10.2	Actin in Nonmuscle Cells	154
10.2.1	Temporal and Spatial Localization of Actin in Plant Cells	154
10.2.2	Biochemistry of Actin	155
10.2.3	Biochemistry of Myosins	157
10.3	Force-Generating Reactions Involving Actin	157
10.3.1	Actomyosin	157
10.3.2	Polymerization of Actin Filaments	158
10.4	Actin-Based Motility	158
10.4.1	Cytoplasmic Streaming	159
10.4.2	Chloroplast Movements	162

10.4.3	Cell Plate Reorientation in <i>Allium</i>	163	12.5	A Kinetic Description of Regulation	189
10.4.4	Secretion of Vesicles Involved in Tip Growth and Auxin-Induced Growth	163	12.5.1	Early History of Kinetic Studies	189
10.4.5	Contractile Vacuoles	164	12.5.2	Kinetics of Enzyme Reactions	190
10.5	Role of Actin in Membrane Transport	164	12.5.3	Kinetics of Diffusion and Dehydration	194
10.6	Summary	164	12.5.4	A Thermodynamic Analysis of the Signal-to-Noise Problem	196
10.7	Questions	164	12.6	Ca ²⁺ Signaling System	196
11	Tubulin and Microtubule-Mediated Processes		12.7	Mechanics of Doing Experiments to Test the Importance of Ca ²⁺ as a Second Messenger	197
11.1	Discovery of Microtubules in Cilia and Flagella and the Mechanism of Movement	165	12.8	Specific Signaling Systems in Plants Involving Ca ²⁺	198
11.2	Microtubules in Nonflagellated or Nonciliated Cells and the Discovery of Tubulin	168	12.8.1	Ca ²⁺ -Induced Secretion in Barley Aleurone Cells	198
11.2.1	Temporal and Spatial Localization of Microtubules in Animal and Plant Cells	170	12.8.2	Excitation-Cessation of Streaming Coupling in Characean Internodal Cells	198
11.2.2	Characterization of Microtubule-Associated Motor Proteins	173	12.8.3	Regulation of Turgor in Cells	199
11.3	Force-Generating Reactions Involving Tubulin	174	12.9	Phosphatidylinositol Signaling System	204
11.3.1	Sliding	174	12.9.1	Components of the System	204
11.3.2	Polymerization/Depolymerization	174	12.9.2	Phosphatidylinositol Signaling in Guard Cell Movement	204
11.4	Tubulin-Based Motility	175	12.10	The Role of Ions in Cells	205
11.5	Microtubules and Cell Shape	175	12.11	Summary	206
11.5.1	Apical Meristems	175	12.12	Questions	206
11.5.2	Tracheary Elements	176	13	Chloroplasts	
11.5.3	Guard Cells	177	13.1	Discovery of Chloroplasts and Photosynthesis	207
11.5.4	Extracellular Matrix of <i>Oocystis</i>	178	13.1.1	Discovery of Photosynthesis	208
11.5.5	Mechanism of Microtubule-Mediated Cellulose Orientation	178	13.1.2	Discovery and Structure of Chloroplasts	210
11.5.6	Tip-Growing Cells	178	13.2	Isolation of Chloroplasts	214
11.6	Various Stimuli Affect Microtubule Orientation	179	13.3	Composition of the Chloroplasts	214
11.7	Microtubules and Cytoplasmic Structure	180	13.4	Thermodynamics and Bioenergetics in Photosynthesis	215
11.8	Intermediate Filaments	180	13.4.1	Laws of Thermodynamics	216
11.9	Centrin-Based Motility	180	13.4.2	Molecular Free Energy of Some Photosynthetic Processes	217
11.10	Tensegrity in Cells	181	13.4.3	Molecular Free Energy of Oxidation-Reduction Reactions	218
11.11	Summary	181	13.5	Organization of the Thylakoid Membrane and the Light Reactions of Photosynthesis	221
11.12	Questions	181	13.5.1	Photosystem Complexes	223
12	Cell Signaling		13.5.2	Cytochrome _{b₆-f} Complex	224
12.1	The Scope of Cell Regulation	183	13.5.3	ATP Synthase	224
12.2	What Is Stimulus-Response Coupling?	184	13.5.4	Light Reactions of Photosynthesis	225
12.3	Receptors	186	13.6	Physiological, Biochemical, and Structural Adaptations of the Light Reactions	227
12.4	Cardiac Muscle as a Paradigm for Understanding the Basics of Stimulus-Response Coupling	187	13.7	Fixation of Carbon	228

13.8	Reduction of Nitrate and the Activation of Sulfate	230	16.6	Cell Cycle	280
13.9	Chloroplast Movements and Photosynthesis	230	16.7	Chromosomal Replication	281
13.10	Genetic System of Plastids	232	16.8	Transcription	282
13.11	Biogenesis of Plastids	234	16.9	Nucleolus and Ribosome Formation	285
13.12	Summary	235	16.10	Summary	287
13.13	Questions	236	16.11	Questions	287
14. Mitochondria			17. Ribosomes and Proteins		
14.1	Discovery of the Mitochondria and Their Function	237	17.1	Nucleic Acids and Protein Synthesis	289
14.1.1	History of the Study of Respiration	237	17.2	Protein Synthesis	290
14.1.2	History of the Structural Studies in Mitochondria	238	17.3	Protein Activity	294
14.2	Isolation of Mitochondria	240	17.4	Protein Targeting	294
14.3	Composition of Mitochondria	241	17.5	Protein-Protein Interactions	295
14.3.1	Proteins	241	17.6	Protein Degradation	295
14.3.2	Lipids	241	17.7	Structure of Proteins	296
14.4	Cellular Geography of Mitochondria	241	17.8	Functions of Proteins	296
14.5	Chemical Foundation of Respiration	242	17.9	Techniques of Protein Purification	296
14.5.1	Fitness of ATP as a Chemical Energy Transducer	242	17.10	Plants as Bioreactors to Produce Proteins for Vaccines	297
14.5.2	Glycolysis	246	17.11	Summary	297
14.5.3	Cellular Respiration	247	17.12	Questions	297
14.6	Other Functions of the Mitochondria	254	18. The Origin of Life		
14.7	Genetic System in Mitochondria	255	18.1	Spontaneous Generation	299
14.8	Biogenesis of Mitochondria	256	18.2	Concept of Vitalism	300
14.9	Summary	257	18.3	The Origin of the Universe	301
14.10	Questions	257	18.4	Geochemistry of the Early Earth	303
15. Origin of Organelles			18.5	Prebiotic Evolution	304
15.1	Autogenous Origin of Organelles	259	18.6	The Earliest Darwinian Ancestor and the Last Common Ancestor	309
15.2	Endosymbiotic Origin of Chloroplasts and Mitochondria	260	18.7	Diversity in the Biological World	315
15.3	Origin of Peroxisomes, Centrioles, and Cilia	262	18.8	The Origin of Consciousness	316
15.4	Ongoing Process of Endosymbiosis	263	18.9	Concept of Time	317
15.5	Primordial Host Cell	263	18.10	Summary	317
15.6	Symbiotic DNA	264	18.11	Questions	318
15.7	Summary	264	19. Cell Division		
15.8	Questions	265	19.1	Mitosis	319
16. The Nucleus			19.1.1	Prophase	320
16.1	The Discovery of the Nucleus and Its Role in Heredity, Systematics, and Development	267	19.1.2	Prometaphase	321
16.2	Isolation of Nuclei	271	19.1.3	Metaphase	324
16.3	Structure of the Nuclear Envelope and Matrix	271	19.1.4	Anaphase	326
16.4	Chemistry of Chromatin	273	19.1.5	Telophase	331
16.5	Morphology of Chromatin	277	19.2	Regulation of Mitosis	331
			19.3	Energetics of Mitosis	331
			19.4	Division of Organelles	332
			19.5	Cytokinesis	332
			19.5.1	Cell Plate Formation	332
			19.5.2	Isolation of Cell Plates	334
			19.5.3	Orientation of the Cell Plate	336
			19.6	Summary	338
			19.7	Questions	338

20. Extracellular Matrix	
20.1 Relationship of the Extracellular Matrix of Plant and Animal Cells	339
20.2 Isolation of the Extracellular Matrix of Plants	341
20.3 Chemical Composition and Architecture of the Extracellular Matrix	341
20.4 Extracellular Matrix–Plasma Membrane–Cytoskeletal Continuum	343
20.5 Biogenesis of the Extracellular Matrix	344
20.5.1 Plasma Membrane	344
20.5.2 Cytoskeleton	345
20.5.3 Endomembrane System	345
20.5.4 Self-Assembly of the Extracellular Matrix	346
20.6 Permeability of the Extracellular Matrix	346
20.7 Mechanical Properties of the Extracellular Matrix	346
20.8 Cell Expansion	349
20.8.1 Forces, Pressures, and Stresses and Their Relationship to Strain	349
20.9 Summary	355
20.10 Epilog	355
20.11 Questions	356
Appendix 1 SI Units, Constants, Variables, and Geometric Formulae	357
Appendix 2 A Cell Biologist's View of Non-Newtonian Physics	363
Appendix 3 Calculation of the Total Transverse Force and Its Relation to Stress	371
Appendix 4 Laboratory Exercises	373
Index	383