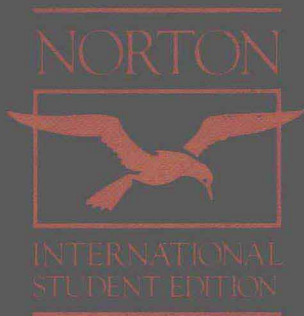


# BIOLOGICAL SCIENCE

FOURTH EDITION



WILLIAM T. KEETON  
JAMES L. GOULD

**WILLIAM T. KEETON**

CORNELL UNIVERSITY

**JAMES L. GOULD**

PRINCETON UNIVERSITY

WITH CAROL GRANT GOULD

# **BIOLOGICAL SCIENCE**

**FOURTH EDITION**

W • W • NORTON

NEW YORK • LONDON

Copyright © 1986, 1980, 1979, 1978, 1972, 1967 by W. W. Norton & Company, Inc.  
ALL RIGHTS RESERVED.  
PRINTED IN THE UNITED STATES OF AMERICA.

Since this page cannot legibly accommodate all the copyright notices, pages  
A20–A26 constitute an extension of the copyright page.

This book is composed in Aster. Composition by New England Typographic  
Service, Inc. Manufacturing by R. R. Donnelley & Sons, Company. Book design  
by Antonina Krass.

FOURTH EDITION

Library of Congress Cataloging in Publication Data

Keeton, William T.  
Biological science.  
Includes index.  
I. Biology. I. Gould, James L., 1945-  
II. Gould, Carol Grant. III. Title.  
QH308.K38 1986 574 86-5262  
ISBN 0-393-95385-8

Cover photo by Nicholas Foster, The Image Bank.

W. W. Norton & Company Inc., 500 Fifth Avenue, New York, N.Y. 10110  
W. W. Norton & Company Ltd., 10 Coptic Street, London WC1A 1PU  
5 6 7 8 9 0

# BIOLOGICAL SCIENCE

# CONTENTS IN BRIEF

## *Preface*

### *Chapter 1* INTRODUCTION

## **PART I THE CHEMICAL AND CELLULAR BASIS OF LIFE**

### *Chapter 2* SOME SIMPLE CHEMISTRY

### *Chapter 3* THE CHEMISTRY OF LIFE

### *Chapter 4* AT THE BOUNDARY OF THE CELL

### *Chapter 5* INSIDE THE CELL

### *Chapter 6* MULTICELLULAR ORGANIZATION AND THE DIVERSITY OF ORGANISMS

### *Chapter 7* ENERGY TRANSFORMATIONS: RESPIRATION AND OTHER CATABOLIC PATHWAYS

### *Chapter 8* ENERGY TRANSFORMATIONS: PHOTOSYNTHESIS

## **PART II THE BIOLOGY OF ORGANISMS**

### *Chapter 9* NUTRIENT PROCUREMENT AND PROCESSING BY PLANTS AND OTHER AUTOTROPHS

### *Chapter 10* NUTRIENT PROCUREMENT AND PROCESSING BY ANIMALS AND OTHER HETEROTROPHS

### *Chapter 11* GAS EXCHANGE

### *Chapter 12* INTERNAL TRANSPORT IN UNICELLULAR ORGANISMS AND PLANTS

### *Chapter 13* INTERNAL TRANSPORT IN ANIMALS

### *Chapter 14* REGULATION OF BODY FLUIDS

### *Chapter 15* CHEMICAL CONTROL IN PLANTS

*Chapter 16* CHEMICAL CONTROL IN ANIMALS

*Chapter 17* HORMONES AND VERTEBRATE REPRODUCTION

*Chapter 18* NERVOUS CONTROL

*Chapter 19* SENSORY RECEPTION AND PROCESSING

*Chapter 20* EFFECTORS

*Chapter 21* ANIMAL BEHAVIOR

*Chapter 22* THE EVOLUTION OF BEHAVIOR

### **PART III THE PERPETUATION OF LIFE**

*Chapter 23* CELLULAR REPRODUCTION

*Chapter 24* MENDELIAN GENETICS

*Chapter 25* NON-MENDELIAN PATTERNS OF INHERITANCE

*Chapter 26* THE STRUCTURE AND REPLICATION OF DNA

*Chapter 27* TRANSCRIPTION AND TRANSLATION

*Chapter 28* EXTRACHROMOSOMAL INHERITANCE

*Chapter 29* CONTROL OF GENE EXPRESSION

*Chapter 30* IMMUNOLOGY AND THE MECHANISMS OF GENETIC VARIABILITY

*Chapter 31* ORGANIZATION OF DEVELOPMENT IN ANIMALS AND PLANTS

*Chapter 32* MECHANISMS OF DEVELOPMENT: DIFFERENTIATION AND PATTERN FORMATION

### **PART IV THE BIOLOGY OF POPULATIONS AND COMMUNITIES**

*Chapter 33* EVOLUTION: ADAPTATION

*Chapter 34* EVOLUTION: SPECIATION AND PHYLOGENY

*Chapter 35* ECOLOGY

*Chapter 36* ECOSYSTEMS AND BIOGEOGRAPHY

### **PART V THE GENESIS AND DIVERSITY OF ORGANISMS**

*Chapter 37* THE ORIGIN AND EARLY EVOLUTION OF LIFE

*Chapter 38* VIRUSES AND MONERA

*Chapter 39* THE PROTISTAN KINGDOM

*Chapter 40* THE PLANT KINGDOM

*Chapter 41* THE FUNGAL KINGDOM

*Chapter 42* THE ANIMAL KINGDOM: INVERTEBRATES

*Chapter 43* THE ANIMAL KINGDOM: CHORDATES

## PREFACE

Few challenges are more exciting and rewarding than teaching introductory biology. A teacher has the responsibility of presenting the essentials of a dynamic and critically relevant discipline to students of widely differing backgrounds and needs, of providing an informed lay understanding for many, and at the same time erecting a secure foundation for more advanced courses for others. Bill Keeton was a pioneer of the integrated approach to teaching introductory biology; his lucid and authoritative text has become the standard against which other books are judged. The success of this exceptional scientist and teacher was based both on his skill at exposition and on his conception of the field, in which he viewed the variety of living things in terms of the similarities and differences in the evolutionary adaptations they have undergone. This perspective led him to treat plants and animals together, comparing and contrasting the problems they face and the solutions that have evolved. For him, biology was never a series of special issues, a litany of social and environmental concerns, or an encyclopedia of premedical facts.

Despite the enduring excellence of *Biological Science*, it is no surprise that six years after the publication of the Third Edition an up-to-date presentation of modern biology is again needed. In preparing this Fourth Edition, we have been very fortunate to have a book of such obvious excellence from which to work.

We had three main objectives in revising: to improve the clarity of the presentation wherever possible, adding more intuitive explanations and more functional examples and thus making even the most complex subject matter accessible to a wider range of students; to keep the book manageably brief, which sometimes required the abbreviation or deletion of less essential topics; and to bring the book up to date in both depth and scope, so that it would reflect new discoveries and the shifting emphases in the advanced courses for which it may be the student's primary introduction. In particular, we wished to reinforce the evolutionary theme in all parts of the text, and to provide more intuitive molecular explanations of the mechanisms of biology in all chapters. From our own experience and the comments of other teachers of introductory biology, it was clear that the content of every chapter had to be reviewed for accuracy, emphasis, and effectiveness. In the end, every chapter benefited from this process: several were heavily revised and many of the longer chapters were divided into shorter, more manageable ones. Here, in brief, are some of the more important changes:

1. Chapter 1, the introduction, focuses new attention on the historical context in which modern biology developed, the role of intuition in formulating hypotheses, and the distinction between evolution as a process and natural selection as a mechanism.



2. Chapter 2, on simple chemistry, emphasizes the role of electrons in energy storage and release. The presentation of weak bonds—particularly the important concept of electronegativity—provides a groundwork for the later discussion of enzyme function.

3. Chapter 3, on the chemistry of life, now presents a brief, largely intuitive introduction to equilibrium constants that is particularly helpful in understanding how coupled reactions work. There is a new discussion of how the active sites of enzymes function to weaken the appropriate bonds in substrate molecules.

4. In Chapter 4, which focuses on the cell membrane, new descriptions of how the different sorts of microscopes work will enable students to interpret the many EM photographs in the book more easily. A more intuitive presentation of diffusion and osmosis complements the traditional explication. The biggest change has been in the added emphasis on the cell membrane itself, particularly the forces that stabilize it and the way its channels and gates work to regulate the movement of chemicals into and out of the cell. This discussion permits a more molecular presentation of nerve transmission, hormone action, organelle function (including the electron-transport chain), and fluid regulation in later chapters. The description of endocytosis has been enriched by a discussion of coated pits, with the LDL receptor as the primary example.

5. Chapter 5, on the interior of the cell, now presents an updated and expanded discussion of how newly synthesized proteins are labeled, packaged, and shipped by cellular organelles—particularly the ER and the Golgi. There is now explicit treatment of the microtubular lattice and a more extensive discussion of the endosymbiotic hypothesis.

6. In Chapter 6, on multicellular organization, the most important change has been the addition of a major discussion of cell-to-cell adhesion, including desmosomes and gap junctions.

7. In Chapters 7 and 8, on energy transformations, respiration is now discussed before photosynthesis; this order has an evolutionary logic, since fermentation probably appeared even before cyclic photosynthesis, but its primary advantage is pedagogical: respiration is easier to understand, and its basic features are virtually identical to those of the more complex chemistry of photosynthesis. It is now possible to teach glycolysis intuitively from a thermodynamic perspective, or as a series of chemical changes. New margin illustrations allow the interested student to follow the molecular alterations of glycolysis step by step, while the text outlines the thermodynamic considerations. The chemiosmotic hypothesis in respiration now receives central attention, and is

presented both thermodynamically and anatomically. The treatment of photosynthesis has undergone similar changes, and focuses on its evolution, intuitive thermodynamics, and fascinating anatomy. Of the hundreds of illustrations added or modified to improve the visual presentation of ideas throughout the text, we are particularly pleased with the many new drawings in these two chapters.

8. The chapters on whole-organism physiology (Chapters 9–14) have undergone a number of small but important additions and improvements, most apparent in the new drawings of fluid flow and tissue growth in monocots and dicots, the sections on the evolution and comparative physiology of hearts and circulatory systems, and the treatments of liver and kidney function. As in all the cases in which we have added a molecular emphasis, we believe these details provide a more satisfying, unifying, and comprehensible picture of the life processes they elucidate.

9. The chapters dealing with hormonal control (Chapters 15–17) emphasize the molecular bases of hormone action, second-messenger strategies like that of the calcium-calmodulin system, local chemical mediators and other hormone-like molecules, and the evolution of hormones.

10. The chapters on neurobiology and effectors (Chapters 18–20) have been reorganized and rewritten to reflect a more modern emphasis on molecular mechanisms and the functional issues that relate to sensation and movement. The discussions of interneurons, habituation, and simple circuits use *Aplysia* as their primary example, to complement the extensive treatment of the human CNS. There is new emphasis on how sensory information is processed to extract patterns of shape and movement in the visual world. The discussion of brain evolution has been brought into line with current thinking.

11. Chapter 21, the first of two chapters on behavior, deals with the mechanisms of innate behavior and of learning, and ties these mechanisms to the neurobiology that underlies them; the chapter ends with a discussion of a prime example of the interplay of instinct and learning: bird navigation. Chapter 22 deals with the less mechanistic, more evolutionary aspects of behavior, often called behavioral ecology. Bringing together material formerly divided among several chapters, this discussion treats in one place the concepts of niche and habitat, kin selection and reciprocal altruism, communication, and the social behavior of insects, birds, and mammals (including humans).

12. The genetics and development chapters of Part III required extensive revision to keep pace with the most important new research findings in molecular biology; many more changes have been made in these chapters than can possibly



be mentioned here. Some alterations were strictly pedagogic, such as the reworking of the presentation and accompanying illustrations of mitosis and meiosis in Chapter 23, on cellular reproduction. Also in that chapter, we have added a discussion of the evolution of cell division and sexual recombination, as well as a molecular view of recombination. The genetics chapters (Chapters 24 and 25) have undergone many small changes to improve clarity. They now include new discussions of complementation tests, trihybrid crosses, statistical tests, and the molecular basis of mutation.

13. The chapters on the flow of information in cells (Chapters 26–30) are the most heavily revised in Part III. Our presentation of DNA replication and repair, transcription, messenger RNA “processing” and translation is largely new, and constitutes a modern molecular treatment of these subjects that is eminently suitable for an introductory course. Here, as elsewhere, material most appropriate for majors or advanced students, such as the discussion “Replication of the *E. coli* chromosome,” is presented in self-contained boxes that supplement the more general treatment in the text. Extrachromosomal inheritance is now presented in a separate chapter (Chapter 28), which incorporates new or heavily revised discussions of organelle heredity, the mechanisms of viral replication, and recombinant DNA technology. The chapter on the control of gene expression (Chapter 29) is almost entirely new, containing discussions of negative and positive transcriptional control, a revised presentation of the *lac* operon, two boxes on advanced topics (“How control substances bind to DNA” and a particularly well understood example of repression, “The lambda switch”), an exposition of the curious organization of eucaryotic chromosomes, and a modern discussion of cancer and oncogenes. The new chapter on immunology (Chapter 30) features a well-integrated discussion of how B cells and T cells work and interact to produce precisely modulated immune responses. This chapter also includes important discussions of the genetic basis of antibody diversity and of the various mechanisms of genetic variability, including transposition, which may provide the variation necessary for the evolution of novel proteins. Intriguing hypotheses of gene evolution, like that of Gilbert and Blake, are considered.

14. A variety of small improvements have been incorporated into Chapters 31 and 32, on development, but the main revisions are those providing coverage of the mechanistic bases of differentiation and pattern formation. In particular, there is now major treatment of neural development.

15. The first two chapters of Part IV (Chapters 33 and 34) now give more attention than the previous edition to the possible role of chance, and of genetic drift in particular, in evo-

lution. They also provide necessary examples of sympatric speciation and host specificity, and discuss several major controversies among evolutionary biologists; these include the debates over punctuated equilibria and cladistics.

16. The last two chapters of Part IV (Chapters 35 and 36) deal with ecology and biogeography. Many teachers were unhappy with the organization of this material in the Third Edition, with the choice of examples in the sections on ecosystems and community ecology, and with the lack of emphasis on physiological ecology. These criticisms have been taken to heart: the new organization puts material on population size and distribution first in Chapter 35; this is followed by sections on population growth and regulation, and the chapter ends with a discussion of dominance, diversity, stability, and succession. Chapter 36 now begins with a view of the economy of ecosystems—the flow of energy and materials—followed by a new section on the role of the sun in creating worldwide climatic zones. The discussion then focuses on more local factors like mountain ranges, and on the different kinds of biomes. The chapter ends with a consideration of the evolution of biomes and the mechanisms and consequences of species dispersal.

17. The Fourth Edition continues to use Robert H. Whitaker’s five-kingdom classification system, modified to accommodate the new findings on Archaeobacteria. This system and some alternatives are discussed in Chapter 37, which also includes a modernized account of current ideas about the origin and early evolution of life. In the Third Edition the chapters on classification (now Chapters 38–43) were perhaps the most complete in an introductory book, and they are therefore not much changed, except for Chapter 38, on viruses and Monera, which now includes discussions of viroids, prions, and Archaeobacteria. Numerous small changes in the classification of higher animals have been necessary; the sections dealing with the evolution of vertebrates, primates in particular, have also been carefully updated to reflect current thinking.

Throughout the Fourth Edition, our general pedagogical strategy has been to begin a chapter—or, more often, a set of chapters—with an overview of what is to come, thus providing an initial evolutionary or functional outline to help the student place the sections that follow in a useful context. Several new summary diagrams and discussions reflect this approach.

We decided early on to keep the general chapter order of the Third Edition. No single sequence is ideal, and the present one has the advantage of familiarity. We have, however, made every effort to make the parts stand on their own, so that they can be taught in different orders. At Princeton,

for example, we teach Part IV immediately after Part I, followed by Part III, Part V, and then Part II. It is a testament to the flexibility of the Third Edition that we have no difficulty using the book with our idiosyncratic order, and the Fourth Edition should prove even more adaptable. Teachers who wish to keep their presentations of plants and animals separate will find that the new chapter divisions facilitate this approach.

This brief listing of the major changes in the Fourth Edition should not be taken to imply that other parts of the text have escaped careful scrutiny. On the contrary, an intense re-evaluation has gone on throughout the book. Despite such exhaustive efforts, there will be parts of the book that do not reflect the most recent advances by the time students use the text. Not only will new developments have occurred in the interim between writing and publication but, lacking a crystal ball, we may have failed to recognize the significance of developments already taking place. For a text author, this is as unfortunate as it is unavoidable, but it is not all bad for students, since it reflects the vitality of the field.

A revision of this magnitude of a book with such high standards to maintain would have been impossible without the help of many reviewers. In particular we would like to thank Joseph M. Calvo, Cornell; Robert K. Colwell, Berkeley; Peter Grant, Princeton; Andre T. Jagendorf, Cornell; Carol H. McFadden, Cornell; C. O. Patterson, Texas A & M; Thomas Roos, Dartmouth; Daniel I. Rubenstein, Princeton; Peter M. Shugarman, Southern California; Malcolm Steinberg, Princeton; Volker M. Vogt, Cornell; and Timothy C. Williams, Swarthmore College, for help above and beyond the call of duty. Many other important criticisms were provided by Wayne Aspey, Ohio State; Robert A. Bender, Michigan; Anthony Blackler, Cornell; Robert W. Bouma, Cornell; George

Bowes, Florida; George Cain, Iowa; W. Zacheus Cande, Berkeley; Steven Jay Gould (no relation), Harvard; Richard Hallberg, Iowa State; Steven Heidemann, Michigan State; Paul Hertz, Barnard; Robert P. Higgins, Smithsonian Institution; William Hodos, Maryland; Anthony R. Kaney, Bryn Mawr College; Joseph Levine, Boston College; William M. Lewis, Colorado; Karel F. Liem, Harvard; Ellis R. Loew, Cornell; Ross J. MacIntyre, Cornell; Peter Marler, Rockefeller; Mitch Masters, Oregon; Kenneth Miller, Brown; John Neess, Wisconsin; Michael Newlon, Iowa; Maggie T. Pennington, College of Charleston; David Pilbeam, Harvard; Patricia J. Pukilla, North Carolina; Robert Savage, Swarthmore College; John A. Schmitt, Ohio State; David Shappirio, Michigan; Steven D. Skopik, Delaware; Eric Skully, Towson State; James Smiley, College of Charleston; Douglas W. Smith, California, San Diego; Daryl Sweeney, Illinois; and Virginia Utermohlen, Cornell. The many new and uniformly excellent pictures and drawings in the Fourth Edition speak more eloquently than can we of the contribution of Ruth Mandel, our photo editor, and of Michael Reingold, the artist. The consistently high quality of the copy was maintained by the unparalleled vigilance and good judgment of Esther Jacobson, with help from Nancy Palmquist. Roy Tedoff and Fred Bidgood made the impossibly complicated task of book production at least seem feasible. Finally, the greatest contribution to both the rigor and the aesthetic appeal of this text was made by our indefatigable editor, James D. Jordan, whose remorseless insistence on clarity of exposition shows on every page. To all of these individuals, our heartfelt thanks.

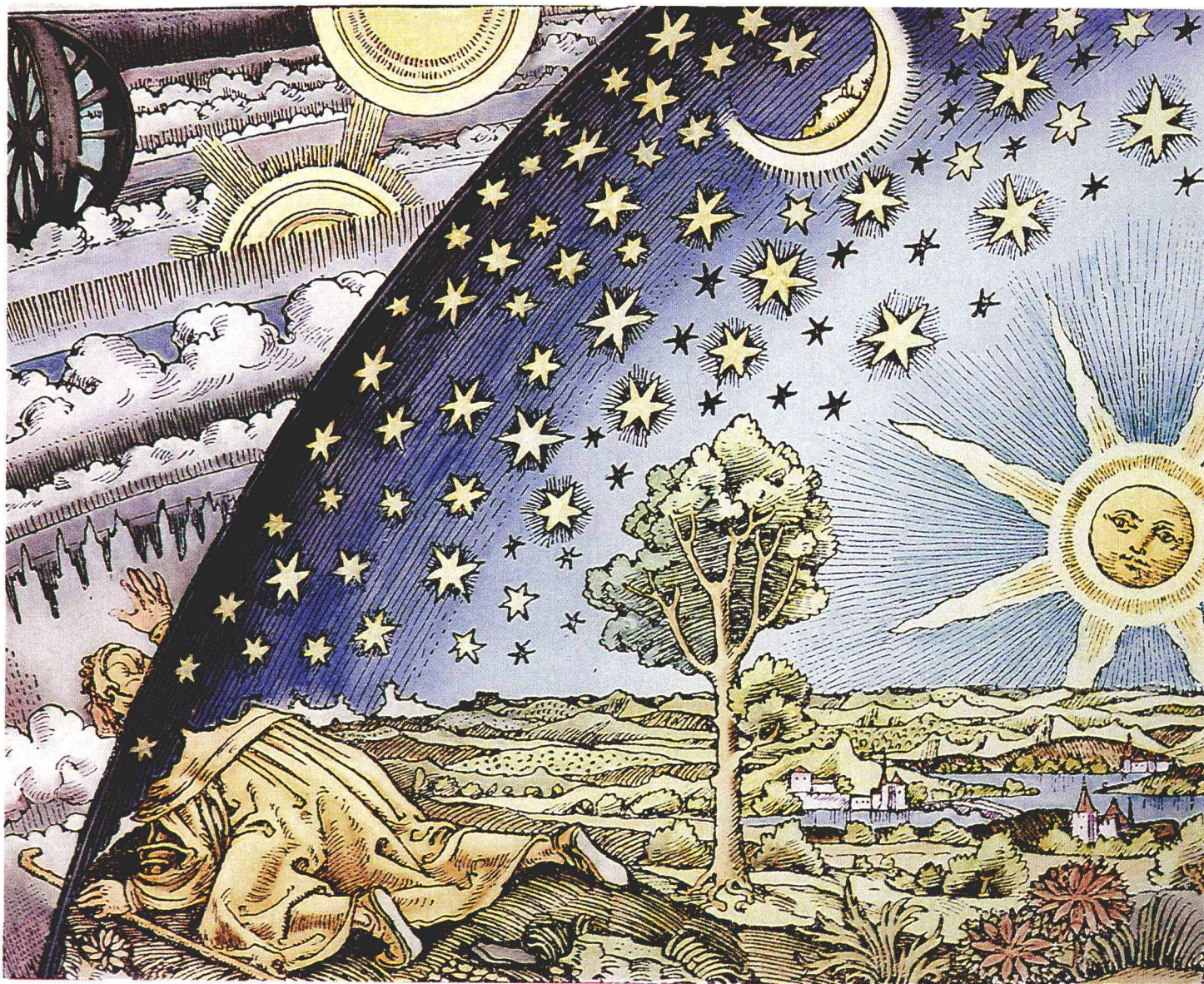
J.L.G.

C.G.G.

Princeton, New Jersey  
October 1985

## **BIOLOGICAL SCIENCE**







# CONTENTS

<i>Preface</i>	xxi	<b>PART I THE CHEMICAL AND CELLULAR BASIS OF LIFE</b>	23
<i>Chapter 1</i> INTRODUCTION	1		
<b>LIFE</b>	1	<i>Chapter 2</i> SOME SIMPLE CHEMISTRY	25
<b>THE SCIENTIFIC METHOD</b>	2	<b>THE ELEMENTS</b>	25
Formulating hypotheses • Testing hypotheses • The controlled experiment • Intuition • Limitations of the scientific method		ATOMIC STRUCTURE	26
<b>THE RISE OF MODERN BIOLOGICAL SCIENCE</b>	6	The atomic nucleus • The electrons • Electron distribution and the chemical properties of elements • Radioactive decay	
EARLY SCIENCE	6	<b>CHEMICAL BONDS</b>	33
EARLY DISCOVERIES IN ASTRONOMY AND PHYSICS	8	IONIC BONDS	33
THE BEGINNINGS OF MODERN BIOLOGY	11	Acids and bases	
<b>DARWIN'S THEORY</b>	12	COVALENT BONDS	36
THE CONCEPT OF EVOLUTIONARY CHANGE	12	Double and triple bonds • Polar covalent bonds	
THE CONCEPT OF NATURAL SELECTION	16	BIOLOGICALLY IMPORTANT WEAK BONDS	38
MODERN BIOLOGY	20	Strong versus weak bonds • Hydrogen bonds • Weaker interactions • The role of weak bonds	

<b>SOME IMPORTANT INORGANIC MOLECULES</b>	41	<b>STRUCTURE OF THE CELL MEMBRANE</b>	94
WATER	41	THE DAVSON-DANIELLI MODEL	95
Water as a solvent • Special physical properties of water • The role of water in regulating environmental temperature		THE FLUID-MOSAIC MODEL	96
CARBON DIOXIDE	45	<i>Exploring further: Freeze-etching</i>	98
OXYGEN	46	MEMBRANE CHANNELS AND PUMPS	100
		Membrane channels • Membrane pumps	
		ENDOCYTOSIS AND EXOCYTOSIS	105
 <i>Chapter 3 THE CHEMISTRY OF LIFE</i>	47	 <b>CELL WALLS AND COATS</b>	106
<b>SOME SIMPLE ORGANIC CHEMISTRY</b>	47	Cell walls of plants, fungi, and bacteria • The glycocalyx	
CARBOHYDRATES	49	 <i>Chapter 5 INSIDE THE CELL</i>	111
Simple sugars • Disaccharides • Polysaccharides		 <b>SUBCELLULAR ORGANELLES</b>	111
LIPIDS	54	THE NUCLEUS	111
Fats • Phospholipids • Steroids		THE ENDOPLASMIC RETICULUM AND RIBOSOMES	115
PROTEINS	57	THE GOLGI APPARATUS	118
The building blocks and primary structure of proteins • Determining the primary structure • The spatial conformation of proteins • Conjugated proteins		LYSOSOMES	120
<i>Exploring further: Chromatography</i>	62	PEROXISOMES	121
NUCLEIC ACIDS	68	MITOCHONDRIA	122
Deoxyribonucleic acid • Ribonucleic acid		PLASTIDS	122
 <b>CHEMICAL REACTIONS</b>	70	VACUOLES	124
FREE ENERGY	71	MICROFILAMENTS	125
THE EQUILIBRIUM CONSTANT	73	MICROTUBULES	126
ACTIVATION ENERGY	74	THE MICROTRABECULAR LATTICE	127
The effect of catalysts		CENTRIOLES AND BASAL BODIES	128
ENZYMES	76	CILIA AND FLAGELLA	129
Enzyme specificity and the active site • Control of enzyme activity		 <b>EUCARYOTIC VS. PROCARYOTIC CELLS</b>	130
		“TYPICAL” EUCARYOTIC CELLS	131
		PROCARYOTIC CELLS	134
		THE ENDOSYMBIOTIC HYPOTHESIS	134
 <i>Chapter 4 AT THE BOUNDARY OF THE CELL</i>	83	 <i>Chapter 6 MULTICELLULAR ORGANIZATION AND THE DIVERSITY OF ORGANISMS</i>	137
<b>THE CELL THEORY</b>	84	 <b>CELLULAR ADHESION</b>	138
<b>VIEWING THE CELL</b>	85	 <b>PLANT TISSUES</b>	140
<b>FUNCTIONS OF THE CELL MEMBRANE</b>	87	MERISTEMATIC TISSUE	141
DIFFUSION	87	SURFACE TISSUE	141
OSMOSIS	90	FUNDAMENTAL TISSUE	142
<i>Exploring further: Osmotic potential, osmotic pressure, and water potential</i>	92	Parenchyma • Collenchyma • Sclerenchyma • Endodermis	
OSMOSIS AND THE CELL MEMBRANE	93	VASCULAR TISSUE	144
		Xylem • Phloem	



<b>PLANT ORGANS</b>	145	<b>SUMMARY OF RESPIRATION ENERGETICS</b>	187
<b>ANIMAL TISSUES</b>	145	<i>Exploring further: Testing the Mitchell hypothesis</i>	188
EPITHELIUM	146	<b>METABOLISM OF FATS AND PROTEINS</b>	189
CONNECTIVE TISSUE	148	<b>BODY TEMPERATURE AND METABOLIC RATE</b>	190
Blood and lymph • Connective tissue proper • Cartilage • Bone		<b>Chapter 8 ENERGY TRANSFORMATIONS: PHOTOSYNTHESIS</b>	195
MUSCLE	151	<b>EARLY RESEARCH IN PHOTOSYNTHESIS</b>	196
NERVE	151	<b>THE LIGHT REACTIONS: PHOTOPHOSPHORYLATION</b>	199
<b>ANIMAL ORGANS</b>	151	LIGHT AND CHLOROPHYLL	199
<b>THE DIVERSITY OF LIFE</b>	152	CYCLIC PHOTOPHOSPHORYLATION	203
MONERA	154	Electron transport	
Eubacteria • Archaeobacteria		NONCYCLIC PHOTOPHOSPHORYLATION	204
PROTISTA	156	THE ANATOMY OF PHOTOPHOSPHORYLATION	207
The plantlike protists • The animal-like protists		<b>THE DARK REACTIONS: CARBON FIXATION</b>	210
PLANTAE	157	CARBOHYDRATE SYNTHESIS BY THE CALVIN CYCLE	210
Brown algae and red algae • Green algae • Mosses, liverworts, and their relatives • Vascular plants		Photorespiration	
FUNGI	160	<b>THE LEAF AS AN ORGAN OF PHOTOSYNTHESIS</b>	213
ANIMALIA	161	THE ANATOMY OF LEAVES	213
Coelenterates • Flatworms • Molluscs • Annelids • Arthropods • Echinoderms • Chordates		LEAVES WITH KRANZ ANATOMY	214
<b>Chapter 7 ENERGY TRANSFORMATIONS: RESPIRATION AND OTHER CATABOLIC PATHWAYS</b>	167	C <sub>4</sub> PHOTOSYNTHESIS	215
<b>THE FLOW OF ENERGY</b>	167	CRASSULACEAN ACID METABOLISM (CAM)	217
EVOLUTION OF ENERGY TRANSFORMATIONS	168	<b>PART II THE BIOLOGY OF ORGANISMS</b>	219
OXIDATION AND REDUCTION	169	<b>Chapter 9 NUTRIENT PROCUREMENT AND PROCESSING BY PLANTS AND OTHER AUTOTROPHS</b>	221
ADENOSINE TRIPHOSPHATE (ATP)	170	<b>NUTRIENT REQUIREMENTS OF GREEN PLANTS</b>	222
<b>CELLULAR METABOLISM</b>	171	RAW MATERIALS FOR PHOTOSYNTHESIS	222
ANAEROBIC METABOLISM	172	MINERAL NUTRITION	223
Glycolysis (Stage I of respiration) • Fermentation		<b>NUTRIENT PROCUREMENT BY GREEN PLANTS</b>	226
<i>Exploring further: Coupled reactions</i>	176	ROOTS AS ORGANS OF PROCUREMENT	227
AEROBIC METABOLISM (RESPIRATION)	179	Root structure • Absorption of nutrients	
Oxidation of pyruvic acid to acetyl-CoA (Stage II of respiration) • The Krebs citric acid cycle (Stage III of respiration) • The respiratory electron-transport chain (Stage IV of respiration)		NITROGEN FIXATION	234
<i>Exploring further: Regulation of glucose breakdown</i>	183	INSECTIVOROUS GREEN PLANTS	236
THE ANATOMY OF RESPIRATION	184		
Chemiosmotic synthesis of ATP (Stage V of respiration)			

*Chapter 10* NUTRIENT PROCUREMENT AND  
PROCESSING BY ANIMALS AND OTHER  
HETEROTROPHS 238

**NUTRIENT REQUIREMENTS OF  
HETEROTROPHIC ORGANISMS** 238

NUTRIENTS REQUIRED IN BULK 239

VITAMINS 241

Water-soluble vitamins • Fat-soluble vitamins

MINERAL NUTRITION 245

**NUTRIENT PROCUREMENT BY FUNGI** 247

**NUTRIENT PROCUREMENT BY ANIMALS AND  
PROTOZOANS** 248

NUTRIENT PROCUREMENT BY PROTOZOANS 249

NUTRIENT PROCUREMENT BY COELENTERATES 251

NUTRIENT PROCUREMENT BY FLATWORMS 253

ANIMALS WITH COMPLETE DIGESTIVE TRACTS 254

THE DIGESTIVE SYSTEM OF HUMANS AND OTHER VERTEBRATES 258

The oral cavity • The esophagus and the stomach • The small  
intestine • The large intestine

ENZYMATIC DIGESTION IN HUMANS 265

Digestion by saliva • Digestion in the stomach • Digestion in  
the small intestine • Bile

*Exploring further:* The digestion of lactose by human adults 270

*Chapter 11* GAS EXCHANGE 272

**THE PROBLEM** 273

**SOLUTIONS IN TERRESTRIAL PLANTS** 274

LEAVES 274

STEMS AND ROOTS 278

**SOLUTIONS IN AQUATIC ANIMALS** 280

GILLS 281

SOLUTIONS OTHER THAN GILLS 284

**SOLUTIONS IN TERRESTRIAL ANIMALS** 285

LUNGS 285

The swim bladder of fish

TRACHEAL SYSTEMS 292

*Chapter 12* INTERNAL TRANSPORT IN  
UNICELLULAR ORGANISMS AND PLANTS 295

**THE PROBLEM** 295

**ORGANISMS WITHOUT SPECIAL TRANSPORT  
SYSTEMS** 296

**SOLUTIONS IN VASCULAR PLANTS** 297

STRUCTURE OF STEMS 297

Monocot organization • Herbaceous dicot organization •  
Woody dicot organization • Xylem • Phloem

TRANSPORT OF SAP 308

The problem • Capillarity • Root pressure • The cohesion  
theory

TRANSPORT OF SOLUTES 314

Transport of organic solutes • Transport of inorganic solutes •  
Hypotheses of phloem function

*Chapter 13* INTERNAL TRANSPORT IN  
ANIMALS 318

**THE PROBLEM** 318

**CIRCULATION IN INSECTS** 319

**CIRCULATION IN VERTEBRATES** 320

THE CIRCULATORY PATH 320

The circuit in humans • The circuit in other vertebrates

PUMPING OF THE BLOOD 327

The heart • Blood pressure and rate of flow

*Exploring further:* Measuring blood pressure 330

CAPILLARY FUNCTION 331

*Exploring further:* Thromboembolic and hypertensive disease in  
human beings 334

THE LYMPHATIC SYSTEM 338

**HUMAN BLOOD** 339

COMPOSITION OF THE PLASMA 340

BLOOD CLOTTING 342

*Exploring further:* How does blood clot? 343

LEUKOCYTES AND THEIR FUNCTIONS 344

ERYTHROCYTES AND THEIR FUNCTION 345

HEMOGLOBIN 346

Hemoglobin and its role in the transport of oxygen • The role  
of hemoglobin in transport of carbon dioxide

<i>Chapter 14</i>	REGULATION OF BODY FLUIDS	352	<i>Chapter 16</i>	CHEMICAL CONTROL IN ANIMALS	403
	THE EXTRACELLULAR FLUIDS OF PLANTS	353		HORMONES IN INVERTEBRATES	403
	THE VERTEBRATE LIVER	355		HORMONES IN VERTEBRATES	406
	The liver's role in regulation of the blood-sugar level • The liver's role in the metabolism of lipids and amino acids • A summary of the liver's functions			HORMONAL CONTROL OF DIGESTION	406
	THE PROBLEM OF EXCRETION AND SALT AND WATER BALANCE IN ANIMALS	358		THE PANCREAS AS AN ENDOCRINE ORGAN	407
	THE PROBLEM FOR AQUATIC ANIMALS	359		THE ADRENALS	412
	Marine invertebrates • Freshwater animals • Marine vertebrates			The adrenal medulla • The adrenal cortex	
	THE PROBLEM FOR TERRESTRIAL ANIMALS	362		THE THYROID	416
	EXCRETORY MECHANISMS IN ANIMALS	362		THE PARATHYROIDS	418
	CONTRACTILE VACUOLES	362		THE THYMUS	419
	FLAME-CELL SYSTEMS	364		THE PITUITARY AND THE HYPOTHALAMUS	419
	NEPHRIDIA OF EARTHWORMS	365		The posterior pituitary • The anterior pituitary • The control function of the hypothalamus	
	MALPIGHIAN TUBULES	366		THE PINEAL	423
	THE VERTEBRATE KIDNEY	367		MECHANISMS OF HORMONAL ACTION	424
	Structure of the kidney • The formation of urine • Special excretory adaptations of vertebrates			REGULATION OF GENE EXPRESSION	426
	<i>Exploring further:</i> The kidneys as a factor in high blood pressure	368		SECOND MESSENGERS	426
	THE CELLULAR BASIS OF ACTIVE TRANSPORT OF IONS	375		The role of cyclic AMP • Ions as second messengers	
	The sodium-potassium pump			INTERACTION OF SEVERAL HORMONES	431
<i>Chapter 15</i>	CHEMICAL CONTROL IN PLANTS	378		LOCAL CHEMICAL MEDIATORS	431
	HORMONES AND PLANT GROWTH	379		Histamine • Prostaglandins • Endorphins	
	AUXINS	380		THE EVOLUTION OF HORMONES	433
	Auxins and phototropism of shoots • Cellular basis of auxin action • Auxins and the geotropism of shoots • Auxins and inhibition of lateral buds • Auxins and fruit development • Auxins and leaf abscission • Auxins and cell division • Chemical weed control		<i>Chapter 17</i>	HORMONES AND VERTEBRATE REPRODUCTION	434
	GIBBERELLINS	390		THE PROCESS OF SEXUAL REPRODUCTION	434
	CYTOKININS	391		THE HUMAN REPRODUCTIVE SYSTEM	437
	INHIBITORS	392		THE REPRODUCTIVE SYSTEM OF THE HUMAN MALE	437
	ETHYLENE	393		HORMONAL CONTROL OF SEXUAL DEVELOPMENT IN THE MALE	440
	CONTROL OF FLOWERING	395		THE REPRODUCTIVE SYSTEM OF THE HUMAN FEMALE	441
	PHOTOPERIODISM AND FLOWERING	395		HORMONAL CONTROL OF THE FEMALE REPRODUCTIVE CYCLE	443
	IS THERE A FLOWERING HORMONE?	397		HORMONAL CONTROL OF PREGNANCY	448
	DETECTION OF THE PHOTOPERIOD	399		HORMONAL CONTROL OF PARTURITION AND LACTATION	449