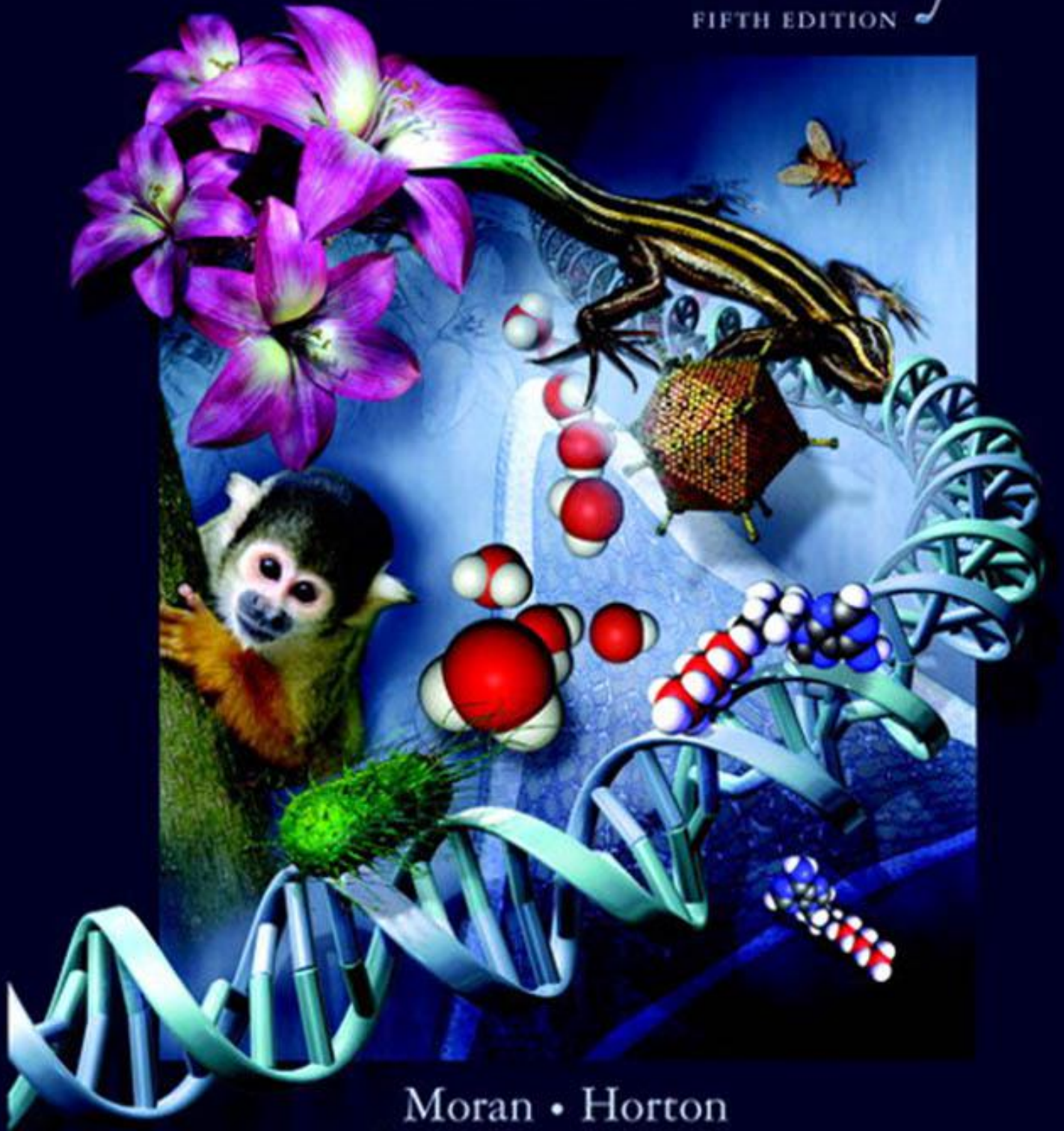
PRINCIPLES OF
Biochemistry
FIFTH EDITION



Moran • Horton
Scrimgeour • Perry

This page intentionally left blank

Principles of Biochemistry

This page intentionally left blank

Principles of Biochemistry

Fifth Edition

Laurence A. Moran
University of Toronto

H. Robert Horton
North Carolina State University

K. Gray Scrimgeour
University of Toronto

Marc D. Perry
University of Toronto

PEARSON

Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montreál Toronto
Delhi Mexico City Sao Pauló Sydney Hong Kong Seoul Singapore Taipei Tokyo

Editor in Chief: Adam Jaworski
Executive Editor: Jeanne Zalesky
Marketing Manager: Erin Gardner
Project Editor: Jennifer Hart
Associate Editor: Jessica Neumann
Editorial Assistant: Lisa Tarabokjia
Marketing Assistant: Nicola Houston
Vice President, Executive Director of Development: Carol Truehart
Developmental Editor: Michael Sypes
Managing Editor, Chemistry and Geosciences: Gina M. Cheselka
Project Manager, Science: Wendy Perez
Senior Technical Art Specialist: Connie Long
Art Studios: Mark Landis Illustrations
/Jonathan Parrish
/2064 Design—Greg Gambino
Image Resource Manager: Maya Melenchuk
Photo Researcher: Eric Schrader
Art Manager: Marilyn Perry
Interior/Cover Designer: Tamara Newnam
Media Project Manager: Shannon Kong
Senior Manufacturing and Operations Manager: Nick Sklitsis
Operations Specialist: Maura Zaldivar
Composition/Full Service: Nesbitt Graphics, Inc.

Cover Illustration: Quade Paul, Echo Medical Media
Cover Image Credit: Monkey adapted from Simone van den Berg/Shutterstock

Credits and acknowledgments borrowed from other sources and reproduced, with permission, in this textbook appear on page 767.

Library of Congress Cataloging-in-Publication Data
Principles of biochemistry / H. Robert Horton ... [et al]. — 5th ed.
p. cm.
ISBN 0-321-70733-8
1. Biochemistry. I. Horton, H. Robert, 1935-
QP514.2.P745 2012
612'.015—dc23

2011019987

ISBN 10: 0-321-70733-8
ISBN 13: 978-0-321-70733-8
1 2 3 4 5 6 7 8 9 10—DOW—16 15 14 13 12

PEARSON

www.pearsonhighered.com

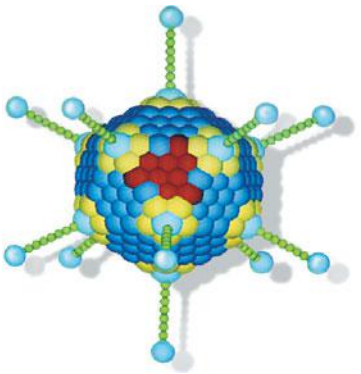
Science should be as simple as possible,
but not simpler.

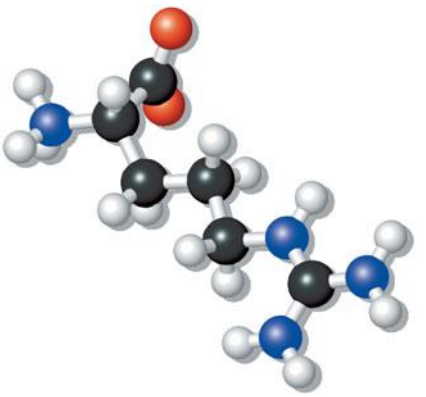
– Albert Einstein

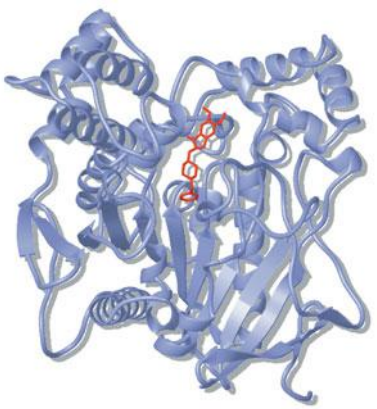
This page intentionally left blank

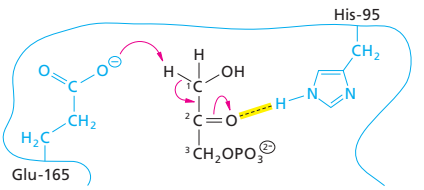
Brief Contents

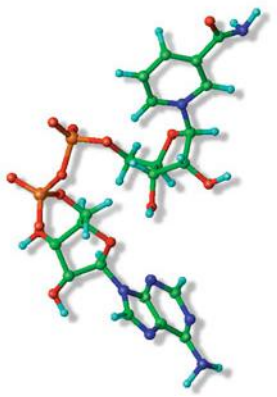
Contents

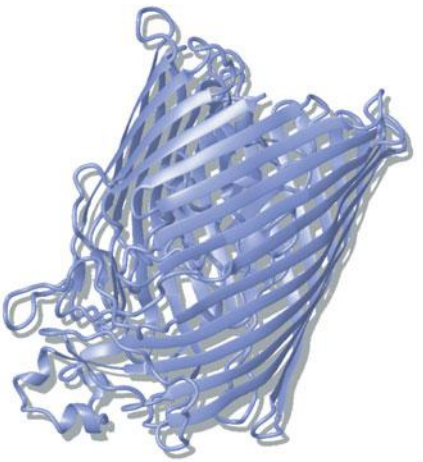






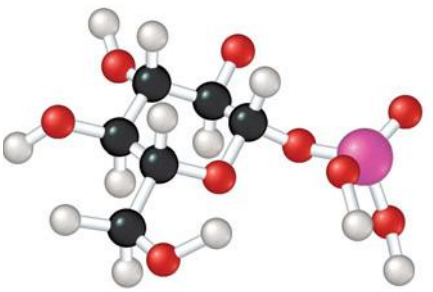


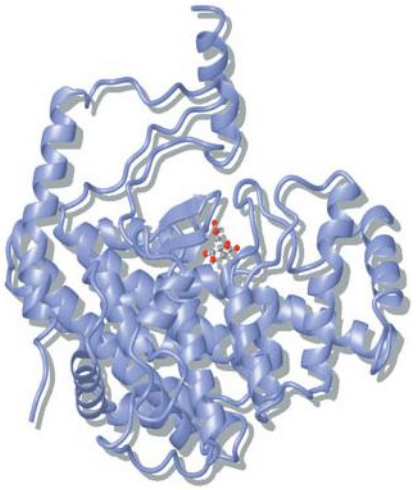




PART THREE

Metabolism and Bioenergetics

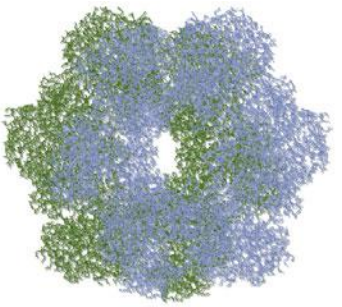




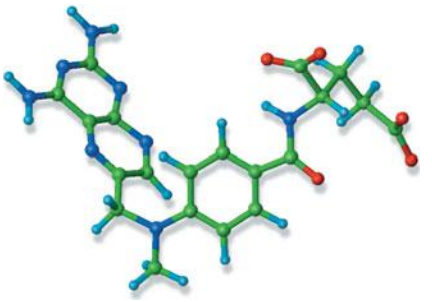
13 The Citric Acid Cycle 385

14 Electron Transport and ATP Synthesis 417

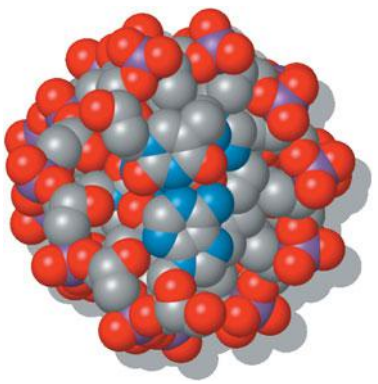
16 Lipid Metabolism 475



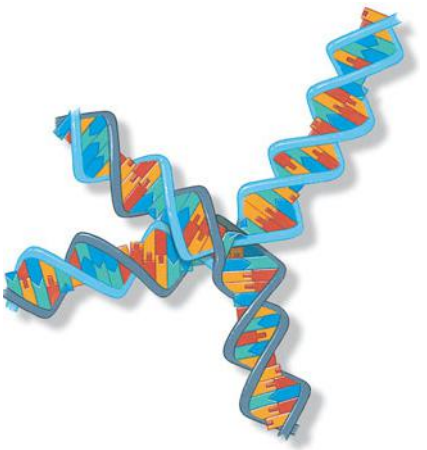
17 Amino Acid Metabolism 514



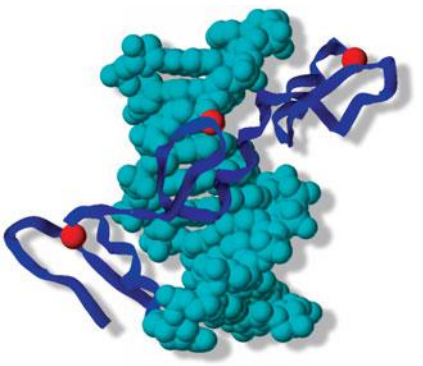
18 Nucleotide Metabolism 550

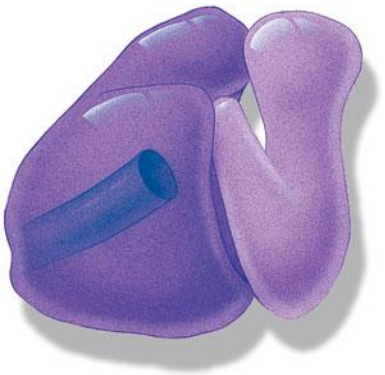


20 DNA Replication, Repair, and Recombination 601



21 Transcription and RNA Processing 633





To the Student

Welcome to biochemistry—the study of life at the molecular level. As you venture into this exciting and dynamic discipline, you'll discover many new and wonderful things. You'll learn how some enzymes can catalyze chemical reactions at speeds close to theoretical limits—reactions that would otherwise occur only at imperceptibly low rates. You'll learn about the forces that maintain biomolecular structure and how even some of the weakest of those forces make life possible. You'll also learn how biochemistry has thousands of applications in day-to-day life—in medicine, drug design, nutrition, forensic science, agriculture, and manufacturing. In short, you'll begin a journey of discovery about how biochemistry makes life both possible and better.

Before we begin, we would like to offer a few words of advice:

Don't just memorize facts; instead, understand principles

In this book, we have tried to identify the most important principles of biochemistry. Because the knowledge base of biochemistry is continuously expanding, we must grasp the underlying themes of this science in order to understand it. This textbook is designed to expand on the foundation you have acquired in your chemistry and biology courses and to provide you with a biochemical framework that will allow you to understand new phenomena as you meet them.

Be prepared to learn a new vocabulary

An understanding of biochemical facts requires that you learn a biochemical vocabulary. This vocabulary includes the chemical structures of a number of key molecules. These molecules are grouped into families based on their structures and functions. You will also learn how to distinguish among members of each family and how small molecules combine to form macromolecules such as proteins and nucleic acids.

Test your understanding

True mastery of biochemistry lies with learning how to apply your knowledge and how to solve problems. Each chapter concludes with a set of carefully crafted problems that test your understanding of core principles. Many of these problems are mini case studies that present the problem within the context of a real biochemical puzzle.

For more practice, we are pleased to refer you to *The Study Guide for Principles of Biochemistry* by Scott Lefler and Allen Scism which presents a variety of supplementary questions that you may find helpful. You will also find additional problems on TheChemistryPlace® for *Principles of Biochemistry* (**http://www.chemplace.com**).

Learn to visualize in 3-D

Biochemicals are three-dimensional objects. Understanding what happens in a biochemical reaction at the molecular level requires that you be able to "see" what happens in three dimensions. We present the structures of simple molecules in several different ways in order to illustrate their three-dimensional conformation. In addition to the art in the book, you will find many animations and interactive molecular models on the website. We strongly suggest you look at these movies and do the exercises that accompany them as well as participate in the molecular visualization tutorials.

Feedback

Finally, please let us know of any errors or omissions you encounter as you use this text. Tell us what you would like to see in the next edition. With your help we will continue to evolve this work into an even more useful tool. Our e-mail addresses are at the end of the Preface. Good luck, and enjoy!

This page intentionally left blank

Preface

Given the breadth of coverage and diversity of ways to present topics in biochemistry, we have tried to make the text as modular as possible to allow for greater flexibility and organization. Each large topic resides in its own section. Reaction mechanisms are often separated from the main thread of the text and can be passed over by those who prefer not to cover this level of detail. The text is extensively cross-referenced to make it easier for you to reorganize the chapters and for students to see the interrelationships among various topics and to drill down to deeper levels of understanding.

We built the book explicitly for the beginning student taking a first course in biochemistry with the aim of encouraging students to think critically and to appreciate scientific knowledge for its own sake. Parts One and Two lay a solid foundation of chemical knowledge that will help students understand, rather than merely memorize, the dynamics of metabolic and genetic processes. These sections assume that students have taken prerequisite courses in general and organic chemistry and have acquired a rudimentary knowledge of the organic chemistry of carboxylic acids, amines, alcohols, and aldehydes. Even so, key functional groups and chemical properties of each type of biomolecule are carefully explained as their structures and functions are presented.

We also assume that students have previously taken a course in biology where they have learned about evolution, cell biology, genetics, and the diversity of life on this planet. We offer brief refreshers on these topics wherever possible.

New to this Edition

We are grateful for all the input we received on the first four editions of this text. You'll notice the following improvements in this fifth edition:

- **Key Concept** margin notes are provided throughout to highlight key concepts and principles that students must know.
- **Interest Boxes** have been updated and expanded, with 45% new to the fifth edition. We use interest boxes to explain some topics in more detail, to illustrate certain principles with specific examples, to stimulate students curiosity about science, to show applications of biochemistry, and to explain clinical relevance. We have also added a few interests boxes that warn students about misunderstanding and misapplications of biochemistry. Examples include Blood Plasma and Sea Water; Fossil Dating by Amino Acid Racemization; Embryonic and Fetal Hemoglobins; Clean Clothes; The Perfect Enzyme; Supermouse; The Evolution of a Complex Enzyme; An Egregious Error; Mendels Seed Color Mutant; Oxygen Pollution of Earth's Atmosphere; Extra Virgin Olive Oil; Missing Vitamins; Pulling DNA; and much more.
- New Material has been added throughout, including an improved explanation of early evolution (the Web of Life), more emphasis on protein protein interactions, a new section on intrinsically disordered proteins, and a better description of the distinction between Gibbs free energy changes and reaction rates. We have removed the final chapter on Recombinant DNA Technology and integrated much of that material into earlier chapters. We have added descriptions of a number of new protein structures and integrated them into two major themes: structure-function and multienzyme complexes. The best example is the fatty acid synthase complex in Chapter 16.

  In some cases new material was necessary because recent discoveries have changed our view of some reactions and processes. We now know, for example, that older versions of uric acid catabolism were incorrect, the correct pathway is shown in Figure 18.23.

We have been careful not to add extra detail unless it supports and extends the basic concepts and principles that we have established over the past four editions. Similarly, we do not introduce new subjects unless they illustrate new concepts that were not covered in previous editions. The goal is to keep this textbook focused on the fundamentals that students need to know and prevent it from bloating up into an encyclopedia of mostly irrelevant information that detracts from the main pedagogical goals.

- **Selected Readings** after each chapter reflect the most current literature and these have been updated and extended where necessary. We have added over 120 new references and deleted many that are no longer appropriate. Although we have always included references to the pedagogical literature, you will note that we have added quite a few more references of this type. Students now have easy access to these papers and they are often more informative than advanced papers in the purely scientific literature.
- **Art** is an important component of a good textbook. Our art program has been extensively revised, with many new photos to illustrate concepts explained in the text; new and updated ribbon art, and improved versions of many figures. Many of the new photos are designed to attract and/or hold the students attention. They can be powerful memory aids and some of them are used to lighten up the subject in a way that is rarely seen in other textbooks (see page 204). We believe that the look and feel of the book has been much improved, making it more appealing to students without sacrificing any of the rigor and accuracy that has been a hallmark of previous editions.

A focus on principles

There are, in essence, two kinds of biochemistry textbooks: those for reference and those for teaching. It is difficult for one book to be both as it is those same thickets of detail sought by the professional that ensnare the struggling novice on his or her first trip through the forest. This text is unapologetically a text for teaching. It has been designed to foster student understanding and is not an encyclopedia of biochemistry. This book focuses unwaveringly on teaching basic principles and concepts, each principle supported by carefully chosen examples. We really do try to get students to see the forest and not the trees!

Because of this focus, the material in this book can be covered in a two-semester course without having to tell students to skip certain chapters or certain sections. The book is also suitable for a one-semester course that concentrates on certain aspects of biochemistry where some subjects are not covered. Instructors can be confident that the core principles and concepts are explained thoroughly and correctly.

A focus on chemistry

When we first wrote this text, we decided to take the time to explain in chemical terms the principles that we want to emphasize. In fact, one of these principles is to show students that life obeys the fundamental laws of physics and chemistry. To that end, we offer chemical explanations of most biochemical reactions, including mechanisms that tell students how and why things happen.

We are particularly proud of our explanations of oxidation-reduction reactions since these are extremely important in so many contexts. We describe electron movements in the early chapters, explain reduction potentials in Chapter 10 and use this understanding to teach about chemiosmotic theory and protonmotive force in Chapter 14 (Electron Transport and ATP Synthesis). The concept is reinforced in the chapter on photosynthesis.

A focus on biology

While we emphasize chemistry, we also stress the bio in biochemistry. We point out that biochemical systems evolve and that the reactions that occur in some species are variations on a larger theme. In this edition, we increase our emphasis on the similarities of

prokaryotic and eukaryotic systems while we continue to avoid making generalizations about all organisms based on reactions that occur in a few.

The evolutionary, or comparative, approach to teaching biochemistry focuses attention on fundamental concepts. The evolutionary approach differs in many ways from other pedagogical methods such as an emphasis on fuel metabolism. The evolutionary approach usually begins with a description of simple fundamental principles or pathways or processes. These are often the pathways found in bacteria. As the lesson proceeds, the increasing complexity seen in some other species is explained. At the end of a chapter we are ready to describe the unique features of the process found in complex multicellular species, such as humans.

Our approach entails additional changes that distinguish us from other textbooks. When introducing a new chapter, such as lipid metabolism, amino acid metabolism, and nucleotide metabolism, most other textbooks begin by treating the molecules as potential food for humans. We start with the biosynthesis pathways since those are the ones fundamental to all organisms. Then we describe the degradation pathways and end with an explanation of how they realte to fuel metabolism. This biosynthesis first organization applies to all the major components of a cell (proteins, nucleotides, nucleic acids, lipids, amino acids) except carbohydrates where we continue to describe glycolysis ahead of gluconeogenesis. We do, however, emphasize that gluconeogenesis is the original, primitive pathway and glycolysis evolved later.

This has always been the way DNA replication, transcription, and translation have been taught. In this book we extend this successful strategy to all the other topics in biochemistry. The chapter on photosynthe sis is an excellent example of how it works in practice.

In some cases the emphasis on evolution can lead to a profound appreciation of how complex systems came to exist. Take the citric acid cycle as an example. Students are often told that such a process cannot be the product of evolution because all the parts are needed before the cycle can function. We explain in Section 13.9 how such a pathway can evolve in a stepwise manner.

A focus on accuracy

We are proud of the fact that this is the most scientifically accurate biochemistry textbook.We have gone to great lengths to ensure that our facts are correct and our explanations of basic concepts reflect the modern consensus among active researchers. Our success is due, in large part, to the dedication of our many reviewers and editors.

The emphasis on accuracy means that we check our reactions and our nomenclature against the IUPAC/IUBMB databases. The result is balanced reactions with correct products and substrates and correct chemical nomenclature. For example, we are one of the very few textbooks that show all of the citric acid cycle reactions correctly. Previous editions of this textbook have always scored highly on the Biochemical Howlers website [**bip.cnrs-mrs.fr/bip10/howler.htm**] and we feel confident that this edition will achieve a perfect score!

We take the time and effort to accurately describe some difficult concepts such as Gibbs free energy change in a steady-state situation where most reactions are near-equlibirium reactions ($\Delta G = 0$). We present correct definitions of the Central Dogma of Molecular Biology. We don't avoid genuine areas of scientific controversy such as the validity of the Three Domain Hypothesis or the mechanism of lysozyme.

A focus on structure-function

Biochemistry is a three-dimensional science. Our inclusion of the latest computer generated images is intended to clarify the shape and function of molecules and to leave students with an appreciation for the relationship between the structure and function. Many of the protein images in this edition are new; they have been skillfully prepared by Jonathan Parrish of the University of Alberta.

We offer a number of other opportunities. For those students with access to a computer, we have included Protein Data Bank (PDB) reference numbers for the coordinates

from which all protein images were derived. This allows students to further explore the structures on their own. In addition, we have a gallery of prepared PDB files that students can view using Chime or any other molecular viewer; these are posted on the text's TheChemistryPlace® website [**chemplace.com**] as are animations of key dynamic processes as well as visualization tutorials using Chime.

The emphasis on protein/enzyme structure is a key part of the theme of structure-function that is one of the most important concepts in biochemistry. At various places in this new edition we have added material to emphasize this relationship and to develop it to a greater extent than we have in the past. Some of the most important reactions in the cell, such as the Q-cycle, cannot be properly understood without understanding the structure of the enzyme that catalyzes them. Similarly, understanding the properties of double-stranded DNA is essential to understanding how it serves as the storehouse of biological information.

Walkthrough of features with some visuals

Interests

Biochemistry is at the root of a number of related sciences, including medicine, forensic science, biotechnology, and bioengineering; there are many interesting stories to tell. Throughout the text, you will find boxes that relate biochemistry to other topics. Some of them are intended to be humorous and help students relate to the material.

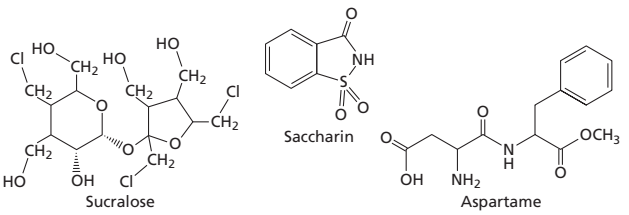
BOX 8.1 THE PROBLEM WITH CATS

One of the characteristics of sugars is that they taste sweet. You certainly know the taste of sucrose and you probably know that fructose and lactose also taste sweet. So do many of the other sugars and their derivatives, although we don't recommend that you go into a biochemistry lab and start tasting all the carbohydrates in those white plastic bottles on the shelves.

Sweetness is not a physical property of molecules. It's a subjective interaction between a chemical and taste receptors in your mouth. There are five different kinds of taste receptors: sweet, sour, salty, bitter, and umami (umami is like the taste of glutamate in monosodium glutamate). In order to trigger the sweet taste, a molecule like sucrose has to bind to the receptor and initiate a response that eventually makes it to your brain. Sucrose elicits a moderately strong response that serves as the standard for sweetness. The response to fructose is almost twice as strong and the response to lactose is only about one-fifth as strong as that of sucrose. Artificial sweeteners such as saccharin (Sweet'N Low®), sucralose (Splenda®), and aspartame (NutraSweet®) bind to the sweetness receptor and cause the sensation of sweetness. They are hundreds of times more sweet than sucrose.

The sweetness receptor is encoded by two genes called *Tas1r2* and *Tas1r3*. We don't know how sucrose and the other ligands bind to this receptor even though this is a very active area of research. In the case of sucrose and the artifical sweeteners, how can such different molecules elicit the taste of sweet?

Cats, including lions, tigers and cheetahs, do not have a functional *Tas1r2* gene. It has been converted to a pseudogene because of a 247 bp deletion in exon 3. It's very likely that your pet cat has never experienced the taste of sweetness. That explains a lot about cats.



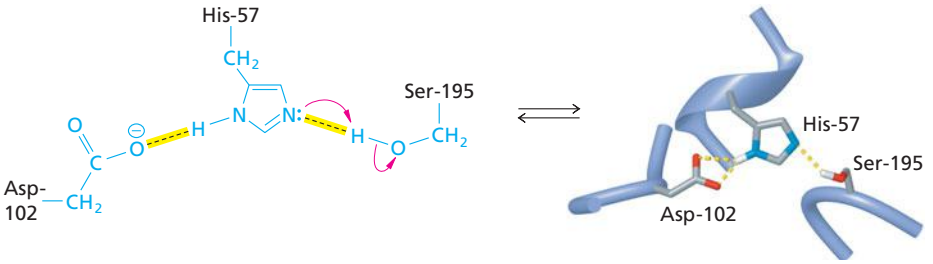
▲ **Cats are carnivores.** They probably can't taste sweetness.

Key Concepts

To help guide students to the information important in each concept, Key Concept notes have been provided in the margin highlighting this information.

Complete Explanations of the Chemistry

There are thousands of metabolic reactions in a typical organism. You might try to memorize them all but eventually you will run out of memory. What's more, memorization will not help you if you encounter something you haven't seen before. In this book, we show you some of the basic mechanisms of enzyme-catalyzed reactions—an extension of what you learned in organic chemistry. If you understand the mechanism, you'll understand the chemistry. You'll have less to memorize, and you'll retain the information more effectively.



KEY CONCEPT

The standard Gibbs free energy change ($\Delta G^{\circ\prime}$) tells us the direction of a reaction when the concentrations of all products and reactants are at 1 M concentration. These conditions will never occur in living cells. Biochemists are only interested in actual Gibbs free energy changes (ΔG), which are usually close to zero. The standard Gibbs free energy change ($\Delta G^{\circ\prime}$) tells us the relative concentrations of reactants and products when the reaction reaches equilibrium.

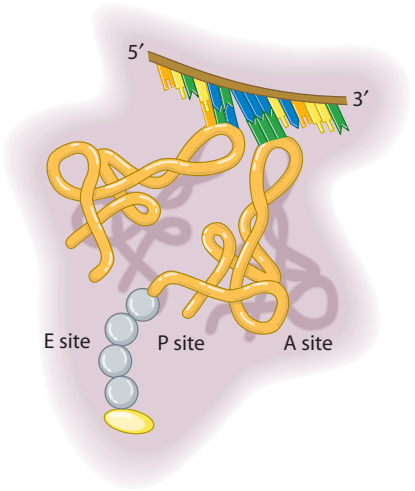
Margin Notes

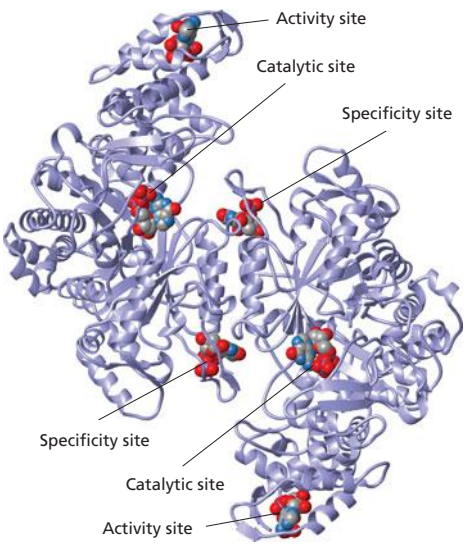
There is a great deal of detail in biochemistry but we want you to see both the forest and the trees. When we need to cross-reference something discussed earlier in the book, or something that we will come back to later, we put it in the margin. Backward references offer a review of concepts you may have forgotten. Forward references will help you see the big picture.

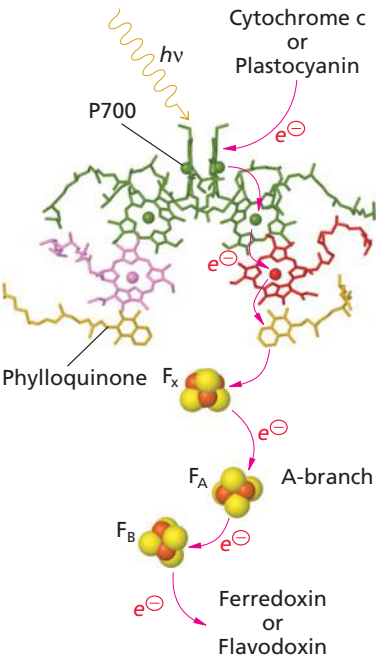
The distinction between the normal flow of information and the Central Dogma of Molecular Biology is explained in Section 1.1 and the introduction to Chapter 21.

Art

Biochemistry is a three-dimensional science and we have placed a great emphasis on helping you visualize abstract concepts and molecules too small to see. We have tried to make illustrative figures both informative and beautiful.







Sample Calculations

Sample Calculations are included throughout the text to provide a problem solving model and illustrate required calculations.

SAMPLE CALCULATION 10.2 Gibbs Free Energy Change

Q: In a rat hepatocyte, the concentrations of ATP, ADP, and P_i are 3.4 mM, 1.3 mM, and 4.8 mM, respectively. Calculate the Gibbs free energy change for hydrolysis of ATP in this cell. How does this compare to the standard free energy change?

A: The actual Gibbs free energy change is calculated according to Equation 10.10.

$$\Delta G_{reaction} = \Delta G^{o\prime}_{reaction} + RT \ln \frac{[ADP][P_i]}{[ATP]} = \Delta G^{\circ}_{reaction} + 2.303\ RT \log \frac{[ADP][P_i]}{[ATP]}$$

When known values and constants are substituted (with concentrations expressed as molar values), assuming pH7.0 and 25°C.

$$\Delta G = -32000\ J\ mol^{-1} + (8.31\ JK^{-1}mol^{-1})(298\ K)\left[2.303 \log \frac{(1.3 \times 10^{-3})(4.8 \times 10^{-3})}{(3.4 \times 10^{-3})}\right]$$

$$\Delta G = -32000\ J\ mol^{-1} + (2480\ J\ mol^{-1})[2.303\ \log(1.8 \times 10^{-3})]$$

$$\Delta G = -32000\ J\ mol^{-1} - 16000\ J\ mol^{-1}$$

$$\Delta G = -48000\ J\ mol^{-1} = -48\ kJ\ mol^{-1}$$

The actual free energy change is about $1^1/_2$ times the standard free energy change.

The Organization

We adopt the metabolism-first strategy of organizing the topics in this book. This means we begin with proteins and enzymes then describe carbohydrates and lipids. This is followed by a description of intermediary metabolism and bioenergetics. The structure of nucleic acids follows the chapter on nucleotide metabolism and the information flow chapters are at the back of the book.

While we believe there are significant advantages to teaching the subjects in this order, we recognize that some instructors prefer to teach information flow earlier in the course. We have tried to make the last four chapters on nucleic acids, DNA replication, transcription, and translation less dependant on the earlier chapters but they do discuss aspects of enzymes that rely on Chapters 4, 5 and 6. Instructors may choose to introduce these last four chapters after a description of enzymes if they wish.

This book has a chapter on coenzymes unlike most other biochemistry textbooks. We believe that it is important to put more emphasis on the role of coenzymes (and vitamins) and that's why we have placed this chapter right after the two chapters on enzymes. We know that most instructors prefer to teach the individual coenzymes when specific examples come up in other contexts. We do that as well. This organization allows instructors to refer back to chapter 7 at whatever point they wish.

Student Supplements

The Study Guide for Principles of Biochemistry

by Scott Lefler
(Arizona State University) and
Allen J. Scism
(Central Missouri State University)

No student should be without this helpful resource. Contents include the following:

- carefully constructed drill problems for each chapter, including short-answer, multiple-choice, and challenge problems
- comprehensive, step-by-step solutions and explanations for all problems
- a remedial chapter that reviews the general and organic chemistry that students require for biochemistry—topics are ingeniously presented in the context of a metabolic pathway
- tables of essential data

Chemistry Place for *Principles of Biochemistry*

An online student tool that includes 3-D modules to help visualize biochemistry and MediaLabs to investigate important issues related to its particular chapter. Please visit the site at **http://www.chemplace.com.**

Acknowledgments

We are grateful to our many talented and thoughtful reviewers who have helped shape this book.

Reviewers who helped in the Fifth Edition:

Accuracy Reviewers

Barry Ganong, Mansfield University
Scott Lefler, Arizona State
Kathleen Nolta, University of Michigan

Content Reviewers

Michelle Chang, University of California, Berkeley
Kathleen Comely, Providence College
Ricky Cox, Murray State University
Michel Goldschmidt-Clermont, University of Geneva
Phil Klebba, University of Oklahoma, Norman
Kristi McQuade, Bradley University
Liz Roberts-Kirchoff, University of Detroit, Mercy
Ashley Spies, University of Illinois
Dylan Taatjes, University of Colorado, Boulder
David Tu, Pennsylvania State University
Jeff Wilkinson, Mississippi State University
Lauren Zapanta, University of Pittsburgh

Reviewers who helped in the Fourth Edition:

Accuracy Reviewers

Neil Haave, University of Alberta
David Watt, University of Kentucky

Content Reviewers

Consuelo Alvarez, Longwood University
Marilee Benore Parsons, University of Michigan
Gary J. Blomquist, University of Nevada, Reno
Albert M. Bobst, University of Cincinnati
Kelly Drew, University of Alaska, Fairbanks
Andrew Feig, Indiana University
Giovanni Gadda, Georgia State University
Donna L. Gosnell, Valdosta State University
Charles Hardin, North Carolina State University
Jane E. Hobson, Kwantlen University College
Ramji L. Khandelwal, University of Saskatchewan
Scott Lefler, Arizona State
Kathleen Nolta, University of Michigan
Jeffrey Schineller, Humboldt State University
Richard Shingles, Johns Hopkins University
Michael A. Sypes, Pennsylvania State University
Martin T. Tuck, Ohio University
Julio F. Turrens, University of South Alabama
David Watt, University of Kentucky
James Zimmerman, Clemson University

Thank you to J. David Rawn who's work laid the foundation for this text. We would also like to thank our colleagues who have previously contributed material for particular chapters and whose careful work still inhabits this book:

Roy Baker, University of Toronto
Roger W. Brownsey, University of British Columbia
Willy Kalt, Agriculture Canada
Robert K. Murray, University of Toronto
Ray Ochs, St. John's University
Morgan Ryan, American Scientist
Frances Sharom, University of Guelph
Malcolm Watford, Rutgers, The State University of New Jersey

Putting this book together was a collaborative effort, and we would like to thank various members of the team who have helped give this project life: Jonathan Parrish, Jay McElroy, Lisa Shoemaker, and the artists of Prentice Hall; Lisa Tarabokjia, Editorial Assistant, Jessica Neumann, Associate Editor, Lisa Pierce, Assistant Editor in charge of supplements, Lauren Layn, Media Editor, Erin Gardner, Marketing Manager; and Wendy Perez, Production Editor. We would also like to thank Jeanne Zalesky, our Executive Editor at Prentice Hall.

Finally, we close with an invitation for feedback. Despite our best efforts (and a terrific track record in the previous editions), there are bound to be mistakes in a work of this size. We are committed to making this the best biochemistry text available; please know that all comments are welcome.

Laurence A. Moran
l.moran@utoronto.ca
Marc D. Perry
marc.perry@utoronto.ca

This page intentionally left blank

About the Authors

Laurence A. Moran

After earning his Ph.D. from Princeton University in 1974, Professor Moran spent four years at the Université de Genève in Switzerland. He has been a member of the Department of Biochemistry at the University of Toronto since 1978, specializing in molecular biology and molecular evolution. His research findings on heat-shock genes have been published in many scholarly journals. (l.moran@utoronto.ca)

H. Robert Horton

Dr. Horton, who received his Ph.D. from the University of Missouri in 1962, is William Neal Reynolds Professor Emeritus and Alumni Distinguished Professor Emeritus in the Department of Biochemistry at North Carolina State University, where he served on the faculty for over 30 years. Most of Professor Horton's research was in protein and enzyme mechanisms.

K. Gray Scrimgeour

Professor Scrimgeour received his doctorate from the University of Washington in 1961 and was a faculty member at the University of Toronto for over 30 years. He is the author of *The Chemistry and Control of Enzymatic Reactions* (1977, Academic Press), and his work on enzymatic systems has been published in more than 50 professional journal articles during the past 40 years. From 1984 to 1992, he was editor of the journal *Biochemistry and Cell Biology*. (gray@scrimgeour.ca)

Marc D. Perry

After earning his Ph.D. from the University of Toronto in 1988, Dr. Perry trained at the University of Colorado, where he studied sex determination in the nematode *C. elegans*. In 1994 he returned to the University of Toronto as a faculty member in the Department of Molecular and Medical Genetics. His research has focused on developmental genetics, meiosis, and bioinformatics. In 2008 he joined the Ontario Institute for Cancer Research. (marc.perry@utoronto.ca)

New problems and solutions for the fifth edition were created by Laurence A. Moran, University of Toronto. The remaining problems were created by Drs. Robert N. Lindquist, San Francisco State University, Marc Perry, and Diane M. De Abreu of the University of Toronto.

This page intentionally left blank