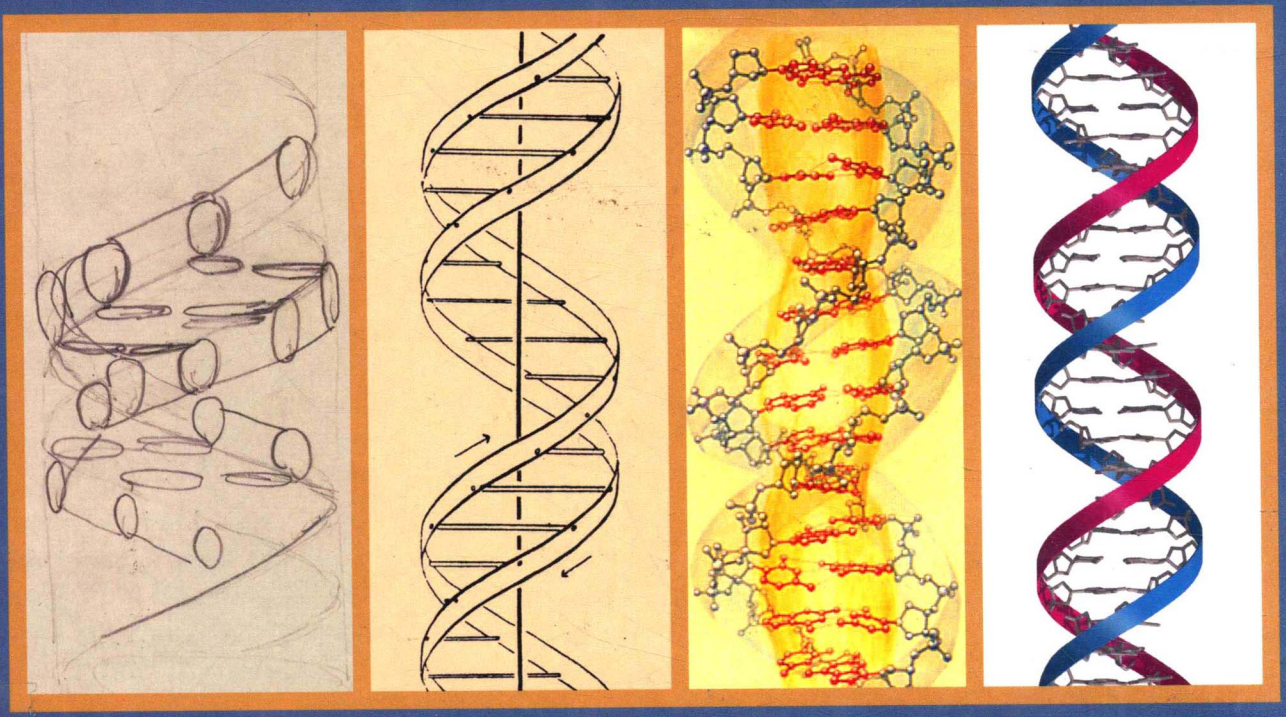
MOLECULAR BIOLOGY OF THE GENE

SEVENTH EDITION



WATSON • BAKER • BELL
GANN • LEVINE • LOSICK

MOLECULAR BIOLOGY OF THE GENE

SEVENTH EDITION

JAMES D. WATSON
Cold Spring Harbor Laboratory

ALEXANDER GANN
Cold Spring Harbor Laboratory

TANIA A. BAKER
Massachusetts Institute of Technology

MICHAEL LEVINE
University of California, Berkeley

STEPHEN P. BELL
Massachusetts Institute of Technology

RICHARD LOSICK
Harvard University

With
STEPHEN C. HARRISON
Harvard Medical School
(Chapter 6: The Structure of Proteins)

PEARSON

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

CSH PRESS
COLD SPRING HARBOR LABORATORY PRESS
Cold Spring Harbor, New York

PEARSON

Editor-in-Chief: Beth Wilbur
Senior Acquisitions Editor: Josh Frost
Executive Director of Development: Deborah Gale
Assistant Editor: Katherine Harrison-Adcock
Managing Editor: Michael Early
Production Project Manager: Lori Newman
Illustrators: Dragonfly Media Group
Manufacturing Buyer: Michael Penne
Director of Marketing: Christy Lesko
Executive Marketing Manager: Lauren Harp
Executive Media Producer: Laura Tommasi
Editorial Media Producer: Lee Ann Doctor
Supervising Media Project Manager: David Chavez
Director of Content Development, MasteringBiology: Natania Mlawer
Content Specialist, MasteringBiology: J. Zane Barlow, PhD

COLD SPRING HARBOR LABORATORY PRESS

Publisher and Sponsoring Editor: John Inglis
Editorial Director: Alexander Gann
Director of Editorial Development: Jan Argentine
Managing Editor and Developmental Editor: Kaaren Janssen
Project Manager: Inez Sialiano
Production Manager: Denise Weiss
Production Editor: Kathleen Bubbeo
Permissions Coordinator: Carol Brown
Crystal Structure Images: Leemor Joshua-Tor and Stephen C. Harrison
Cover Designer: Mike Albano

Front and Back Cover Images: Far left, drawing by Francis Crick, Wellcome Library, London. Second from left, from Watson J.D. and Crick F.H.C. 1953. *Nature* **171:** 737–738. Second from right, Irving Geis illustration. Rights owned by Howard Hughes Medical Institute. Not to be reproduced without permission. Far right, structure by Leemor Joshua-Tor (image prepared with PyMOL).

Credits and acknowledgments for materials borrowed from other sources and reproduced, with permission, in this textbook appear on the appropriate page within the text.

Library of Congress Cataloging-in-Publication Data

Watson, James D.
Molecular biology of the gene / James D. Watson, Cold Spring Harbor Laboratory, Tania A. Baker, Massachusetts Institute of Technology, Alexander Gann, Cold Spring Harbor Laboratory, Michael Levine, University of California, Berkeley, Richard Losick, Harvard University.
pages cm
Includes bibliographical references and index.
ISBN-13: 978-0-321-76243-6 (hardcover (student ed))
ISBN-10: 0-321-76243-6 (hardcover (student ed))
ISBN-13: 978-0-321-90537-6 (paper (a la carte))
ISBN-10: 0-321-90537-7 (paper (a la carte))
[etc.]
1. Molecular biology--Textbooks. 2. Molecular genetics--Textbooks. I. Title.
QH506.M6627 2013
572'.33--dc23

2012046093

2 3 4 5 6 7 8 9 10—DOW—17 16 15 14 13

PEARSON

www.pearsonhighered.com

COLD SPRING HARBOR LABORATORY PRESS
www.cshlpress.org

ISBN 10: 0-321-76243-6 (Student Edition)
ISBN 13: 978-0-321-76243-6 (Student Edition)

ISBN 10: 0-321-90264-5 (Instructor's Review Copy)
ISBN 13: 978-0-321-90264-1 (Instructor's Review Copy)

ISBN 10: 0-321-90537-7 (Books à la Carte Edition)
ISBN 13: 978-0-321-90537-6 (Books à la Carte Edition)

Preface

THE NEW EDITION OF *MOLECULAR BIOLOGY OF THE GENE* appears in this, its 7th edition, on the 60th anniversary of the discovery of the structure of DNA in 1953, an occasion celebrated by our cover design. The double-helical structure, held together by specific pairing between the bases on the two strands, has become one of the iconic images of science. The image of the microscope was perhaps the icon of science in the late 19th century, displaced by the mid 20th century by the graphical representation of the atom with its orbiting electrons. But by the end of the century that image had in turn given way to the double helix.

The field of molecular biology as we understand it today was born out of the discovery of the DNA structure and the agenda for research that that structure immediately provided. The paper by Watson and Crick proposing the double helix ended with a now famous sentence: "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material." The structure suggested how DNA could replicate, opening the way to investigate, in molecular terms, how genes are passed down through generations. It was also immediately apparent that the order of bases along a DNA molecule could represent a "genetic code," and so an attack on that second great mystery of genetics—how genes encode characteristics—could also be launched.

By the time the first edition of *Molecular Biology of the Gene* was published, just 12 years later in 1965, it had been confirmed that DNA replicated in the manner suggested by the model, the genetic code had all but been cracked, and the mechanism by which genes are expressed, and how that expression is regulated, had been established at least in outline. The field of molecular biology was ripe for its first textbook, defining for the first time the curriculum for undergraduate courses in this topic.

Our understanding of the mechanisms underlying these processes has hugely increased over the last 48 years since that first edition, often driven by technological advances, including DNA sequencing (another anniversary this year is the 10th anniversary of completion of the human genome project). The current edition of *Molecular Biology of the Gene* celebrates both the central intellectual framework of the field put in place in that first edition and the extraordinary mechanistic, biological, and evolutionary understanding that has since been achieved.

New to This Edition

There are a number of major changes to the new edition. As well as wide-ranging updates, these include changes in organization, addition of completely new chapters, and the addition of new topics within existing chapters.

- *New Part 2 on the Structure and Study of Macromolecules.* In this new section, each of the three major macromolecules gets its own chapter. The DNA chapter is retained from the previous edition, but what was previously just a short section at the end of that chapter is now expanded into a whole new chapter on the structure of RNA. The chapter on the structure of proteins is completely new and was written for this edition by Stephen Harrison (Harvard University).

- *Techniques chapter moved from the end of the book into Part 2.* This revised and relocated chapter introduces the important techniques that will be referred to throughout the book. In addition to many of the basic techniques of molecular biology, this chapter now includes an updated section on many genomics techniques routinely employed by molecular biologists. Techniques more specialized for particular chapters appear as boxes within those chapters.
- *Completely new chapter on The Origin and Early Evolution of Life.* This chapter shows how the techniques of molecular biology and biochemistry allow us to consider—even reconstruct—how life might have arisen and addresses the prospect of creating life in a test tube (synthetic biology). The chapter also reveals how, even at the very early stages of life, molecular processes were subject to evolution.
- *New material on many aspects of gene regulation.* Part 5 of the book is concerned with gene regulation. In this edition we have introduced significant new topics, such as quorum sensing in bacterial populations, the bacterial CRISPR defense system and piRNAs in animals, the function of Polycomb, and increased discussion of other so-called "epigenetic" mechanisms of gene regulation in higher eukaryotes. The regulation of "paused polymerase" at many genes during animal development and the critical involvement of nucleosome positioning and remodeling at promoters during gene activation are also new topics to this edition.
- *End-of-chapter questions.* Appearing for the first time in this edition, these include both short answer and data analysis questions. The answers to the even-numbered questions are included as Appendix 2 at the back of the book.
- *New experiments and experimental approaches reflecting recent advances in research.* Integrated within the text are new experimental approaches and applications that broaden the horizons of research. These include, for example, a description of how the genetic code can be experimentally expanded to generate novel proteins, creation of a synthetic genome to identify the minimal features required for life, discussion of new genome-wide analysis of nucleosome positioning, experiments on bimodal switches in bacteria, and how new antibacterial drugs are being designed that target the quorum-sensing pathways required for pathogenesis.

Supplements

MasteringBiology www.masteringbiology.com
MasteringBiology is an online homework, tutorial, and assessment system that delivers self-paced tutorials that provide individualized coaching, focus on your course objectives, and are responsive to each student's progress. The Mastering system helps instructors maximize class time with customizable, easy-to-assign, and automatically graded assessments that motivate students to learn outside of class and arrive prepared for lecture. MasteringBiology includes the book's end-of-chapter problems, eighteen 3D structure tutorials, reading quizzes, animations, videos, and a wide variety of activities. The eText is also available through MasteringBiology, providing access to the complete textbook and featuring powerful interactive and customization functions.

Instructor Resource DVD 978-0-321-88342-1/0-321-88342-X
Available free to all adopters, this dual-platform DVD-ROM contains all art and tables from the book in JPEG and PowerPoint in high-resolution (150 dpi) files. The PowerPoint slides include problems formatted for use with Classroom Response Systems. This DVD-ROM also contains an answer key for all of the end-of-chapter Critical Thinking questions included in MasteringBiology.

Transparency Acetates 978-0-321-88341-4/0-321-88341-1
Features approximately 90 four-color illustrations from the text. These transparencies are free to all adopters.

Cold Spring Harbor Laboratory Photographs

As in the previous edition, each part opener includes photographs, some newly added to this edition. These pictures, selected from the archives of Cold Spring Harbor Laboratory, were all taken at the Lab, the great majority during the Symposia hosted there almost every summer since 1933. Captions identify who is in each picture and when it was taken. Many more examples of these historic photos can be found at the CSHL archives website (http://archives.cshl.edu/).

Acknowledgments

Parts of the current edition grew out of an introductory course on molecular biology taught by one of us (RL) at Harvard University, and this author is grateful to Steve Harrison and Jim Wang who contributed to this course in past years. In the case of Steve Harrison, we are additionally indebted to him for writing and illustrating a brand new chapter on protein structure especially for this new edition. No one could be better qualified for such a task, and we are the grateful beneficiaries of—and the book is immeasurably improved by—his contribution.

We are also grateful to Craig Hunter, who earlier wrote the section on the worm for Appendix 1, and to Rob Martienssen, who wrote the section on plants for that same appendix.

We have shown sections of the manuscript to various colleagues and their comments have been extremely helpful. Specifically we thank Katsura Asano, Stephen Blacklow, Jamie Cate, Amy Caudy, Irene Chen, Victoria D'Souza, Richard Ebright, Mike Eisen, Chris Fromme, Brenton Graveley, Chris Hammell, Steve Hahn, Oliver Hobert, Ann Hochschild, Jim Hu, David Jerulzalmi, Leemor Joshua-Tor, Sandy Johnson, Andrew Knoll, Adrian Krainer, Julian Lewis, Sue Lovett, Karolin Luger, Kristen Lynch, Rob Martienssen, Bill McGinnis, Matt Michael, Lily Mirels, Nipam Patel, Mark Ptashne, Danny Reinberg, Dimitar Sasselov, David Shechner, Sarah T. Stewart-Mukhopadhyay, Bruce Stillman, and Jack Szostak.

We also thank those who provided us with figures, or the wherewithal to create them: Sean Carroll, Seth Darst, Paul Fransz, Brenton Graveley, Ann Hochschild, Julian Lewis, Bill McGinnis, Phoebe Rice, Dan Rokhsar, Nori Satoh, Matt Scott, Ali Shilatifard, Peter Sorger, Tom Steitz, Andrzej Stasiak, Dan Voytas, and Steve West.

New to this edition are end-of-chapter questions, provided by Mary Ellen Wiltrout, and we thank her for these efforts that have enhanced the new edition. In addition, Mary Ellen helped with revisions to the DNA repair chapter.

We are indebted to Leemor Joshua-Tor, who so beautifully rendered the majority of the structure figures throughout the book. Her skill and patience are much appreciated.

We are also grateful to those who provided their software[1]: Per Kraulis, Robert Esnouf, Ethan Merritt, Barry Honig, and Warren Delano. Coordinates were obtained from the Protein Data Bank (www.rcsb.org/pdb/), and citations to those who solved each structure are included in the figure legends.

Our art program was again executed by a team from the Dragonfly Media Group, led by Craig Durant. Denise Weiss and Mike Albano produced a beautiful cover design. We thank Clare Bunce and the CSHL Archive for providing the photos for the part openers and for much help tracking them down.

We thank Josh Frost at Pearson who oversaw our efforts and was always on hand to help us out or provide advice. In development at CSHL Press, Jan Argentine provided great support, guidance, and perspective throughout the process. Our heartfelt thanks to Kaaren Janssen who was once again our constant savior—editing and organizing, encouraging and understanding—and unstintingly good-humored even on the darkest days. Inez Sialiano kept track of the output, and Carol Brown dealt with the permissions as efficiently as ever. In production, we relied heavily on the extraordinary efforts and patience

of Kathleen Bubbeo, for which we are most grateful. And we must also thank Denise Weiss, who oversaw production and ensured that the book looked so good by finessing the page layout and creating the design. John Inglis as ever created the environment in which this could all take place.

And once again, we thank our families for putting up with this book for a third time!

JAMES D. WATSON
TANIA A. BAKER
STEPHEN P. BELL
ALEXANDER GANN
MICHAEL LEVINE
RICHARD LOSICK

[1]Per Kraulis granted permission to use MolScript (Kraulis P.J. 1991. MOLSCRIPT: A program to produce both detailed and schematic plots of protein structures. *J. Appl. Cryst.* **24:** 946–950). Robert Esnouf gave permission to use BobScript (Esnouf R.M. 1997. *J. Mol. Graph.* **15:** 132–134). In addition, Ethan Merritt gave us use of Raster3D (Merritt E.A. and Bacon D.J. 1997. Raster3D: Photorealistic molecular graphics. *Methods Enzymol.* **277:** 505–524), and Barry Honig granted permission to use GRASP (Nicolls A., Sharp K.A., and Honig B. 1991. Protein folding and association: Insights from the interfacial and thermodynamic properties of hydrocarbons. *Proteins* **11:** 281–296). Warren DeLano agreed to the use of PyMOL (DeLano W.L. 2002. *The PyMOL Molecular Graphics System*. DeLano Scientific, Palo Alto, California).

About the Authors

JAMES D. WATSON is Chancellor Emeritus at Cold Spring Harbor Laboratory, where he was previously its Director from 1968 to 1993, President from 1994 to 2003, and Chancellor from 2003 to 2007. He spent his undergraduate years at the University of Chicago and received his Ph.D. in 1950 from Indiana University. Between 1950 and 1953, he did postdoctoral research in Copenhagen and Cambridge, England. While at Cambridge, he began the collaboration that resulted in the elucidation of the double-helical structure of DNA in 1953. (For this discovery, Watson, Francis Crick, and Maurice Wilkins were awarded the Nobel Prize in 1962.) Later in 1953, he went to the California Institute of Technology. He moved to Harvard in 1955, where he taught and did research on RNA synthesis and protein synthesis until 1976. He was the first Director of the National Center for Genome Research of the National Institutes of Health from 1989 to 1992. Dr. Watson was sole author of the first, second, and third editions of *Molecular Biology of the Gene*, and a co-author of the fourth, fifth and sixth editions. These were published in 1965, 1970, 1976, 1987, 2003, and 2007, respectively. He is also a co-author of two other textbooks, *Molecular Biology of the Cell* and *Recombinant DNA*, as well as author of the celebrated 1968 memoir, *The Double Helix*, which in 2012 was listed by the Library of Congress as one of the 88 Books That Shaped America.

TANIA A. BAKER is the Head of the Department and Whitehead Professor of Biology at the Massachusetts Institute of Technology and an Investigator of the Howard Hughes Medical Institute. She received a B.S. in biochemistry from the University of Wisconsin, Madison, and a Ph.D. in biochemistry from Stanford University in 1988. Her graduate research was carried out in the laboratory of Professor Arthur Kornberg and focused on mechanisms of initiation of DNA replication. She did postdoctoral research in the laboratory of Dr. Kiyoshi Mizuuchi at the National Institutes of Health, studying the mechanism and regulation of DNA transposition. Her current research explores mechanisms and regulation of genetic recombination, enzyme-catalyzed protein unfolding, and ATP-dependent protein degradation. Professor Baker received the 2001 Eli Lilly Research Award from the American Society of Microbiology and the 2000 MIT School of Science Teaching Prize for Undergraduate Education and is a Fellow of the American Academy of Arts and Sciences since 2004 and was elected to the National Academy of Sciences in 2007. She is co-author (with Arthur Kornberg) of the book *DNA Replication*, Second Edition.

STEPHEN P. BELL is a Professor of Biology at the Massachusetts Institute of Technology and an Investigator of the Howard Hughes Medical Institute. He received B.A. degrees from the Department of Biochemistry, Molecular Biology, and Cell Biology and the Integrated Sciences Program at Northwestern University and a Ph.D. in biochemistry at the University of California, Berkeley, in 1991. His graduate research was carried out in the laboratory of Dr. Robert Tjian and focused on eukaryotic transcription. He did postdoctoral research in the laboratory of Dr. Bruce Stillman at Cold Spring Harbor Laboratory, working on the initiation of eukaryotic DNA replication. His current research focuses on the mechanisms controlling the duplication of eukaryotic chromosomes. Professor Bell received the 2001 ASBMB–Schering Plough Scientific Achievement Award, the

1998 Everett Moore Baker Memorial Award for Excellence in Undergraduate Teaching at MIT, the 2006 MIT School of Science Teaching Award, and the 2009 National Academy of Sciences Molecular Biology Award.

ALEXANDER GANN is the Lita Annenberg Hazen Dean and Professor in the Watson School of Biological Sciences at Cold Spring Harbor Laboratory. He is also a Senior Editor at Cold Spring Harbor Laboratory Press. He received his B.Sc. in microbiology from University College London and a Ph.D. in molecular biology from The University of Edinburgh in 1989. His graduate research was carried out in the laboratory of Noreen Murray and focused on DNA recognition by restriction enzymes. He did postdoctoral research in the laboratory of Mark Ptashne at Harvard, working on transcriptional regulation, and that of Jeremy Brockes at the Ludwig Institute of Cancer Research at University College London, where he worked on newt limb regeneration. He was a Lecturer at Lancaster University, United Kingdom, from 1996 to 1999, before moving to Cold Spring Harbor Laboratory. He is co-author (with Mark Ptashne) of the book *Genes & Signals* (2002) and co-editor (with Jan Witkowski) of *The Annotated and Illustrated Double Helix* (2012).

MICHAEL LEVINE is a Professor of Genetics, Genomics and Development at the University of California, Berkeley, and is also Co-Director of the Center for Integrative Genomics. He received his B.A. from the Department of Genetics at the University of California, Berkeley, and his Ph.D. with Alan Garen in the Department of Molecular Biophysics and Biochemistry from Yale University in 1981. As a Postdoctoral Fellow with Walter Gehring and Gerry Rubin from 1982 to 1984, he studied the molecular genetics of *Drosophila* development. Professor Levine's research group currently studies the gene networks responsible for the gastrulation of the *Drosophila* and *Ciona* (sea squirt) embryos. He holds the F. Williams Chair in Genetics and Development at University of California, Berkeley. He was awarded the Monsanto Prize in Molecular Biology from the National Academy of Sciences in 1996 and was elected to the American Academy of Arts and Sciences in 1996 and the National Academy of Sciences in 1998.

RICHARD LOSICK is the Maria Moors Cabot Professor of Biology, a Harvard College Professor, and a Howard Hughes Medical Institute Professor in the Faculty of Arts and Sciences at Harvard University. He received his A.B. in chemistry at Princeton University and his Ph.D. in biochemistry at the Massachusetts Institute of Technology. Upon completion of his graduate work, Professor Losick was named a Junior Fellow of the Harvard Society of Fellows when he began his studies on RNA polymerase and the regulation of gene transcription in bacteria. Professor Losick is a past Chairman of the Departments of Cellular and Developmental Biology and Molecular and Cellular Biology at Harvard University. He received the Camille and Henry Dreyfus Teacher-Scholar Award and is a member of the National Academy of Sciences, a Fellow of the American Academy of Arts and Sciences, a Fellow of the American Association for the Advancement of Science, a Fellow of the American Academy of Microbiology, a member of the American Philosophical Society, and a former Visiting Scholar of the Phi Beta Kappa Society. Professor Losick is the 2007 winner of the Selman A. Waksman Award of the National Academy of Sciences, a 2009 winner of the Canada Gairdner Award, a 2012 winner of the Louisa Gross Horwitz Prize for Biology or Biochemistry of Columbia University, and a 2012 winner of the Harvard University Fannie Cox Award for Excellence in Science Teaching.

Class Testers and Reviewers

We wish to thank all of the instructors for their thoughtful suggestions and comments on versions of many chapters in this book.

Chapter Reviewers

Ann Aguanno, *Marymount Manhattan College*
David P. Aiello, *Austin College*
Charles F. Austerberry, *Creighton University*
David G. Bear, *University of New Mexico Health Sciences Center*
Margaret E. Beard, *College of the Holy Cross*
Gail S. Begley, *Northeastern University*
Sanford Bernstein, *San Diego State University*
Michael Blaber, *Florida State University*
Nicole Bournias, *California State University, San Bernardino*
John Boyle, *Mississippi State University*
Suzanne Bradshaw, *University of Cincinnati*
John G. Burr, *University of Texas at Dallas*
Michael A. Campbell, *Pennsylvania State University, Erie, The Behrend College*
Aaron Cassill, *University of Texas at San Antonio*
Shirley Coomber, *King's College, University of London*
Anne Cordon, *University of Toronto*
Sumana Datta, *Texas A&M University*
Jeff DeJong, *University of Texas at Dallas*
Jurgen Denecke, *University of Leeds*
Susan M. DiBartolomeis, *Millersville University*
Santosh R. D'Mello, *University of Texas at Dallas*
Robert J. Duronio, *University of North Carolina, Chapel Hill*
Steven W. Edwards, *University of Liverpool*
David Frick, *University of Wisconsin*
Allen Gathman, *Southeast Missouri State University*
Anthony D.M. Glass, *University of British Columbia*
Elliott S. Goldstein, *Arizona State University*
Ann Grens, *Indiana University, South Bend*
Gregory B. Hecht, *Rowan University*
Robert B. Helling, *University of Michigan*
David C. Higgs, *University of Wisconsin, Parkside*
Mark Kainz, *Colgate University*
Gregory M. Kelly, *University of Western Ontario*
Ann Kleinschmidt, *Allegheny College*
Dan Krane, *Wright State University*
Mark Levinthal, *Purdue University*
Gary J. Lindquester, *Rhodes College*
James Lodolce, *Loyola University Chicago*
Curtis Loer, *University of San Diego*
Virginia McDonough, *Hope College*
Michael J. McPherson, *University of Leeds*
Victoria Meller, *Tufts University*
William L. Miller, *North Carolina State University*
Dragana Miskovic, *University of Waterloo*
David Mullin, *Tulane University*
Jeffrey D. Newman, *Lycoming College*
James B. Olesen, *Ball State University*
Anthony J. Otsuka, *Illinois State University*
Karen Palter, *Temple University*
James G. Patton, *Vanderbilt University*
Ian R. Phillips, *Queen Mary, University of London*
Steve Picksley, *University of Bradford*
Debra Pires, *University of California, Los Angeles*
Todd P. Primm, *University of Texas at El Paso*
Phillip E. Ryals, *The University of West Florida*
Eva Sapi, *University of New Haven*
Jon B. Scales, *Midwestern State University*
Michael Schultze, *University of York*
Venkat Sharma, *University of West Florida*

Erica L. Shelley, *University of Toronto at Mississauga*
Elizabeth A. Shephard, *University College, London*
Margaret E. Stevens, *Ripon College*
Akif Uzman, *University of Houston, Downtown*
Quinn Vega, *Montclair State University*
Jeffrey M. Voight, *Albany College of Pharmacy*
Lori L. Wallrath, *University of Iowa*
Robert Wiggers, *Stephen F. Austin State University*
Bruce C. Wightman, *Muhlenberg College*
Bob Zimmermann, *University of Massachusetts*

Class Testers

Charles F. Austerberry, *Creighton University*
Christine E. Bezotté, *Elmira College*
Astrid Helfant, *Hamilton College*
Gerald Joyce, *The Scripps Research Institute*
Jocelyn Krebs, *University of Alaska, Anchorage*
Cran Lucas, *Louisiana State University in Shreveport*
Anthony J. Otsuka, *Illinois State University*
Charles Polson, *Florida Institute of Technology*
Ming-Che Shih, *University of Iowa*

Brief Contents

PART 2: STRUCTURE AND STUDY OF MACROMOLECULES, 45

3 The Importance of Weak and Strong Chemical Bonds, 51

4 The Structure of DNA, 77

PART 3: MAINTENANCE OF THE GENOME, 193

9 The Replication of DNA, 257