CELLS

EDITORS

Benjamin Lewin

Lynne Cassimeris

Vishwanath R. Lingappa

George Plopper

CELLS

LEAD EDITORS

Benjamin Lewin

Lynne Cassimeris
Lehigh University

Vishwanath R. Lingappa
California Pacific Medical Center
Research Institute

George Plopper
Rensselaer Polytechnic Institute

SCIENTIFIC EDITORS

Leslie Pond
Jamie Kass

JONES AND BARTLETT PUBLISHERS
Sudbury, Massachusetts
BOSTON TORONTO LONDON SINGAPORE

World Headquarters

Jones and Bartlett Publishers
40 Tall Pine Drive
Sudbury, MA 01776
978-443-5000
info@jbpub.com
www.jbpub.com

Jones and Bartlett Publishers Canada
6339 Ormindale Way
Mississauga, Ontario L5V 1J2
CANADA

Jones and Bartlett Publishers International
Barb House, Barb Mews
London W6 7PA
UK

Jones and Bartlett's books and products are available through most bookstores and online booksellers. To contact Jones and Bartlett Publishers directly, call 800-832-0034, fax 978-443-8000, or visit our website, www.jbpub.com.
Substantial discounts on bulk quantities of Jones and Bartlett's publications are available to corporations, professional associations, and other qualified organizations. For details and specific discount information, contact the special sales department at Jones and Bartlett via the above contact information or send an email to specialsales@jbpub.com.

Production Credits

Chief Executive Officer: Clayton Jones
Chief Operating Officer: Don W. Jones, Jr.
President, Higher Education and Professional Publishing: Robert W. Holland, Jr.
V.P., Design and Production: Anne Spencer
V.P., Manufacturing and Inventory Control: Therese Connell
V.P., Sales and Marketing: William J. Kane
Acquisitions Editor, Science: Cathleen Sether
Managing Editor, Science: Dean W. DeChambeau
Acquisitions Editor, Science: Shoshanna Grossman
Editorial Assistant, Science: Molly Steinbach
Project Manager: Kent Thompson
Senior Production Editor: Louis C. Bruno, Jr.
Production Assistant: Jennifer M. Ryan
Marketing Manager: Andrea DeFronzo
Interactive Technology Manager: Dawn Mahon Priest
Cover and Text Design: Anne Spencer
Principal Illustrator: Jan VanAarsen
Art Program developed and executed by: Bang Wong, Jan VanAarsen, Andrew Tang, Joanne Haderer Müller
Senior Photo Researcher and Photographer: Kimberly Potvin
Composition: Anne Spencer, John Garland, Philip Regan
Cover Images: © Dr. Gary D. Gaugler/Phototake; © Phototake; © Dennis Kunkel/Phototake
Printing and Binding: Courier Kendallville
Cover Printing: Courier Kendallville

Library of Congress Cataloging-in-Publication Data

Cells / editors, Benjamin Lewin ... [et al.].
p. cm.
ISBN-13: 978-0-7637-3905-8
ISBN-10: 0-7637-3905-7
1. Cells. I. Lewin, Benjamin.
QH581.2.C445 2006
571.6—dc22

2006013055

6048

Printed in the United States of America
11 10 09 08 07 10 9 8 7 6 5 4 3 2

Preface

CELLS is a new cell biology textbook written primarily for advanced undergraduate and graduate students taking their first course in cell biology. It is also a resource for scientists who wish to learn more about topics outside of their field. A key objective in developing this book was to present the content, gleaned from decades of research, in a format that provides students with the information they need to achieve a solid foundation in cell biology without overwhelming them with too much detail. Focusing solely on cell biology allowed the team of contributors, lead editors, and scientific advisors and editors to incorporate the current research in the field, thoroughly cover each topic, and provide ample illustrations of cellular processes at the molecular level, without being too unwieldy.

This book covers the structure, organization, growth, regulation, movements, and interactions of cells, with an emphasis on eukaryotic cells. These topics are presented in 17 chapters grouped into seven parts, beginning with the definition of a cell, continuing on to the components of cells and the regulation of cell functions, and ending with cell diversity. Plant cells and prokaryotic cells are covered in separate chapters to emphasize this diversity while highlighting the properties shared by all cells.

Each chapter was written by one or more experts in the subject area. The material that these scientists provided was reviewed by a panel of advisors, who offered essential input. The lead editors and scientific editors endeavored to keep the big picture and overarching philosophy of the text in focus, while editing the text and illustrations for consistent use of terminology and level of exposition.

The design of *CELLS* is intended to enhance pedagogy. Chapters are divided into sections with declarative titles that emphasize the main points. Each section begins with a set of key concepts that enables readers to grasp the important ideas at the outset. To stimulate students' interest in future work, chapters include a section called "What's next?" that describes some of the interesting questions that researchers are tackling. Key review and research articles have been listed for students interested in the experiments that led to the current understanding of each topic.

The artists, in collaboration with the authors and editors, have developed the illustrations to be as self-explanatory as possible, with such features as "grab and go" figure titles and text boxes that lead the reader through a figure. Liberal use of well-labeled micrographs and molecular structures helps students to recognize cellular components and understand relationships between structure and function. Whenever possible, the schematic figures take into account the relative sizes of molecules. Colors and molecular shapes, the latter based on atomic structures where known, are used in a consistent manner throughout the book.

The print version is integrated with a website, accessible through http://bioscience.jbpub.com/cells, which provides access to related resources that are referenced in the text with symbols such as MBIO : 1-0001. For example, students can refer to the website for additional information on techniques or content from other texts, such as *GENES* by Benjamin Lewin. The website also contains interactive figures, animations, and videos, visual aids that are essential to understanding the dynamic nature of cells. These online images are indicated by the symbol  to the left of figure legends in this book. The interactive figures include micrographs with labels that can be turned on and off as well as atomic structures that can be rotated to facilitate recognition of key features of cells and molecules, respectively. In addition, biochemistry chapters are provided on the website as background material for readers who have not completed coursework in the subject or who wish to brush up on it. The accompanying Instructor's ToolKit includes PowerPoint slides of all figures in *CELLS*, all animations and videos, a large collection of test questions, and lecture outlines based on the key concepts.

We are grateful to all the scientists who made this book possible by providing essential micrographs and other images, as well as the journal and book publishers for permission to reproduce them. The credits are listed in the figure legends. In the case of atomic structure images that we generated from RSCB Protein Data Bank files, the original publications are listed on a separate page.

We welcome suggestions for revisions or corrections, which can be sent to us at info@jbpub.com.

Acknowledgments

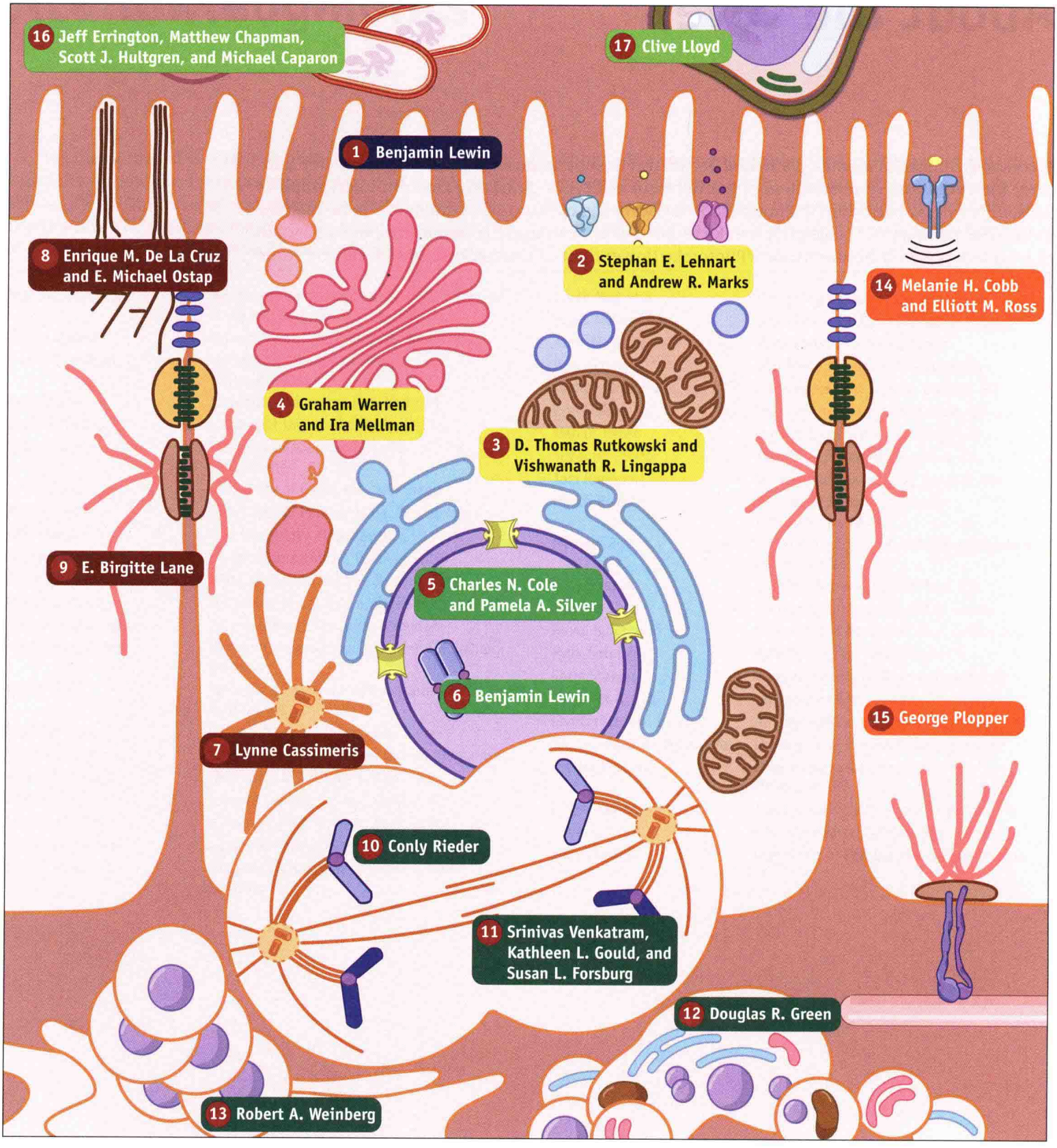
We thank the many scientists who provided advice informally throughout the development of this book; Kent Matlack, whose thoughtful editing and mastery of cell biology, combined with a distinct vision for this book, made him an invaluable member of the team; Leslie Roldan and Linda Ko Ferrigno, who made important contributions in developing and editing the text; Ruth Rose, a talented artist who helped to develop the art program; and the following scientific advisors, who read portions of the text and made many valuable suggestions:

Stephen Adam	Northwestern University Feinberg School of Medicine, Chicago, IL
Tobias Baskin	University of Massachusetts, Amherst
Harris Bernstein	National Institutes of Health, Bethesda, MD
Fred Chang	Columbia University, New York, NY
Louis DeFelice	Vanderbilt University, Nashville, TN
Paola Deprez	Institute of Microbiology–ETH, Zurich, Switzerland
Arshad Desai	University of California, San Diego
Paul De Weer	University of Pennsylvania, Philadelphia
Biff Forbush	Yale University, New Haven, CT
Joseph Gall	Carnegie Institution, Baltimore, MD
Emily Gillett	Harvard Medical School, Boston, MA
Rebecca Heald	University of California, Berkeley
Alistair Hetherington	Bristol University, United Kingdom
Harald Herrmann	German Cancer Research Center, Heidelberg, Germany
Philip Hinds	Tufts–New England Medical Center, Boston, MA
Jer-Yuan Hsu	University of California, San Diego
Martin Humphries	University of Manchester, United Kingdom
James Kadonaga	University of California, San Diego
Randall King	Harvard Medical School, Boston, MA
Roberto Kolter	Harvard Medical School, Boston, MA
Susan LaFlamme	Albany Medical Center, NY
Rudolf Leube	Johannes Gutenberg University, Mainz, Germany
Vivek Malhotra	University of California, San Diego
Frank McCormick	University of California, San Francisco
Akira Nagafuchi	Kumamoto University, Japan
Roel Nusse	Stanford University, Palo Alto, CA
Andrew Osborne	Harvard Medical School, Boston, MA
Erin O'Shea	Harvard University, Cambridge, MA
Marcus Peter	University of Chicago, Chicago, IL
Suzanne Pfeffer	Stanford University, Stanford, CA
Tom Rapoport	Harvard Medical School, Boston, MA
Ulrich Rodeck	Thomas Jefferson University, Philadelphia, PA
Michael Roth	University of Texas Southwestern Medical Center, Dallas
Lucy Shapiro	Stanford University, Stanford, CA
Thomas Shea	University of Massachusetts, Lowell
David Siderovski	University of North Carolina, Chapel Hill
Mark Solomon	Yale University, New Haven, CT
Chris Staiger	Purdue University, West Lafayette, IN
Margaret A. Titus	University of Minnesota, Minneapolis
Livingston Van De Water	Albany Medical Center, NY
Miguel Vicente-Manzanares	University of Virginia, Charlottesville
Patrick Viollier	Case Western Reserve University, Cleveland, OH
Claire Walczak	Indiana University, Bloomington
Junying Yuan	Harvard Medical School, Boston, MA
Sally Zigmond	University of Pennsylvania, Philadelphia

About the cover

A composite image of animal, plant, and bacterial cells superimposed on a phylogenetic tree indicates the evolutionary relatedness of the different cell types. Scanning electron micrograph of *Salmonella typhosa* bacterium © Phototake (left); scanning electron micrograph of a bone marrow stem cell © Dr. Gary D. Gaugler/Phototake (upper right); scanning electron micrograph of a grain of geranium pollen © Dennis Kunkel/Phototake (lower right). Concept: Leslie Pond. Design: Anne Spencer.

Visual table of contents



Contributors

Lead Editors/Authors

Benjamin Lewin founded the journal *Cell* in 1974 and was Editor until 1999. He also founded the Cell Press journals *Neuron*, *Immunity*, and *Molecular Cell*. In 2000, he founded Virtual Text, which was acquired by Jones and Bartlett Publishers in 2005. He is the author of *Genes* and *Essential Genes*.

Lynne Cassimeris is a Professor in the Department of Biological Sciences at Lehigh University in Bethlehem, PA. She studies microtubule assembly dynamics and mitosis.

Vishwanath R. Lingappa is Senior Scientist at Bioconformatics Laboratory, CPMC Research Institute; Chief Technology Officer at Prosetta Corporation; and Emeritus Professor of Physiology, at the University of California, San Francisco. His research is in protein biogenesis. He practices internal medicine as a volunteer physician at San Francisco General Hospital and has coauthored textbooks of physiology and pathophysiology.

George Plopper is an Associate Professor at Rensselaer Polytechnic Institute. He studies signal transduction and cellular behavior induced by extracellular matrix binding.

Authors

Michael Caparon is an Associate Professor in the Department of Molecular Microbiology at Washington University School of Medicine. Research in his laboratory is directed at understanding the complex interactions that occur between pathogenic Gram-positive bacteria and their human hosts during infection.

Matt Chapman is an Assistant Professor at the University of Michigan. His lab studies the function and biogenesis of bacterial amyloid fibers.

Melanie H. Cobb is a Professor in the Graduate Programs in Cell Regulation and Biochemistry and the Department of Pharmacology at the University of Texas Southwestern Medical Center at Dallas. Her group studies regulation and function of protein kinases with an emphasis on MAPK pathways and WNKs.

Charles Cole is a Professor of Biochemistry and of Genetics at Dartmouth Medical School. His interests have included nuclear transport, regulation of cellular transformation and immortalization, RNA metabolism, micro RNAs, and breast cancer.

Enrique M. De La Cruz is an Associate Professor of Molecular Biophysics and Biochemistry at Yale University. His laboratory uses biochemical and biophysical techniques to investigate the mechanisms of actin- and myosin-based motility. His work also focuses on motor properties of RNA helicases.

Jeff Errington is Director of the Institute for Cell and Molecular Biosciences at the University of Newcastle upon Tyne in the United Kingdom. He works on the cell cycle and cell morphogenesis of bacteria.

Susan Forsburg is a Professor in Molecular & Computational Biology at the University of Southern California. Her laboratory studies DNA replication and genome dynamics in the fission yeast *Schizosaccharomyces pombe*.

Kathleen Gould is a Professor of Cell and Developmental Biology at Vanderbilt University School of Medicine and an Investigator of the Howard Hughes Medical Institute. Her laboratory studies the mechanism and regulation of cytokinesis.

Douglas R. Green is the Chair of Immunology at St. Jude Children's Research Hospital in Memphis, TN. His laboratory studies the process of apoptosis and related forms of cell death.

Scott Hultgren is the Helen L. Stoever Professor of Molecular Microbiology at Washington University School of Medicine. His major interests have been in elucidating basic mechanisms of bacterial pathogenesis. His laboratory also is investigating amyloid-like fibers, called curli, which are produced by *Escherichia coli*.

Birgit Lane is Director of the Centre for Molecular Medicine in Singapore, and Cox Professor of Anatomy and Cell Biology at the University of Dundee, Scotland. She studies intermediate filaments, particularly keratins, and the part they play in human disease.

Stephan E. Lehnart is a Research Scientist and Assistant Professor at the Clyde and Helen Wu Center of Molecular Cardiology in the Department of Physiology and Cellular Biophysics at Columbia University. His major research interests are membrane transport mechanisms that control intracellular calcium cycling in the heart and skeletal muscles and that contribute significantly to disease processes.

Clive Lloyd is a project leader at The John Innes Centre, Norwich, UK. He studies the role of the cytoskeleton in plant growth and development.

Andrew R. Marks is the Clyde and Helen Wu Professor of Medicine and Chair and Professor of the Department of Physiology and Cellular Biophysics at Columbia University. He works on how macromolecular signaling complexes regulate ion channel function in muscle and nonmuscle systems. He is a member of the Institute of Medicine of the National Academy of Sciences, American Academy of Arts and Sciences, and the National Academy of Sciences.

Ira Mellman is Sterling Professor and Chair of the Department of Cell Biology at Yale University School of Medicine, and the Editor-in-Chief of *The Journal of Cell Biology*. His laboratory has long been involved with elucidating fundamental mechanisms of membrane traffic on the endocytic pathway, especially as it relates to antigen processing and presentation by dendritic cells and to the generation of polarized membrane domains in epithelial cells.

E. Michael Ostap is an Associate Professor at the University of Pennsylvania School of Medicine and is a member of the Pennsylvania Muscle Institute. His laboratory uses cell biological, biochemical, and biophysical techniques to investigate the mechanisms of cell motility. His work is currently focused on the study of unconventional myosins.

Conly Rieder is a Senior Research Scientist and Chief of the Wadsworth Center's Laboratory of Cell Regulation. The Wadsworth Center is a research arm of the New York State Department of Health. He is also a Professor in the Department of Biomedical Sciences, State University of New York at Albany. Dr. Rieder has spent over 30 years researching how cells divide.

Elliott M. Ross is a Professor in the Graduate Programs in Molecular Biophysics and Cell Regulation and the Department of Pharmacology at the University of Texas Southwestern Medical Center in Dallas. His group studies information processing in G protein signaling networks.

Tom Rutkowski is a postdoctoral associate for the Howard Hughes Medical Institute at the University of Michigan Medical Center. He studies the cellular adaptive response to protein misfolding stress in development and disease.

Pamela Silver is a Professor of Systems Biology at Harvard Medical School. Her interests have included nuclear transport, organization of the genome, RNA dynamics, and synthetic biology.

Srinivas Venkatram is an Assistant Professor of Biological Sciences at the University of the Pacific and a former Research Associate of the HHMI in the laboratory of Kathy Gould. His current research interests include understanding the cell cycle-regulated assembly and disassembly of microtubule-organizing centers and microtubules.

Graham Warren is a Professor of Cell Biology at Yale Medical School, and his laboratory studies the structure, function, and biogenesis of the Golgi apparatus.

Robert A. Weinberg is the Daniel K. Ludwig and American Cancer Society Professor for Cancer Research at the Massachusetts Institute of Technology and a founding member of the Whitehead Institute for Biomedical Research. His research is focused on the molecular mechanisms that control cell proliferation and the formation of tumors.

Abbreviations

A	Adenine or adenosine
ADP	Adenosine diphosphate
AMP	Adenosine monophosphate
cAMP	Cyclic AMP
ATP	Adenosine triphosphate
ATPase	Adenosine triphosphatase
bp	Base pair(s)
C	Cytidine or cytosine
cDNA	Complementary DNA
CDP	Cytidine diphosphate
CMP	Cytidine monophosphate
CTP	Cytidine triphosphate
DNA	Deoxyribonucleic acid
DNAase	Deoxyribonuclease
G	Guanine or guanosine
GDP	Guanosine diphosphate
GlcNAc	N-Acetyl-D-glucosamine
GMP	Guanosine monophosphate
GTP	Guanosine triphosphate
ΔG	Free energy change
kb	Kilobases or kilobase pairs
Mb	Megabases or megabase pairs
mRNA	Messenger RNA
MW	Molecular weight
Pi	Inorganic phosphate
PPi	Inorganic pyrophosphate
RNA	Ribonucleic acid
RNAase	Ribonuclease
rRNA	Ribosomal RNA
tRNA	Transfer RNA
T	Thymine or thymidine
U	Uracil
UDP	Uridine diphosphate
UMP	Uridine monophosphate
UTP	Uridine triphosphate

Prefix (Abbreviation)	Multiple
mega (M)	10^6
kilo (k)	10^3
deci (d)	10^{-1}
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}
nano (n)	10^{-9}
pico (p)	10^{-12}

Units	
Å	Angstrom
D or Da	Dalton
g	Gram
h or hr	Hour
M	Molar concentration
m	Meter
m or min	Minute
N	Newton
S	Svedberg unit
s or sec	Second
v	Volt

Amino acids		
A	Ala	Alanine
C	Cys	Cysteine
D	Asp	Aspartic acid
E	Glu	Glutamic acid
F	Phe	Phenylalanine
G	Gly	Glycine
H	His	Histidine
I	Ile	Isoleucine
K	Lys	Lysine
L	Leu	Leucine
M	Met	Methionine
N	Asn	Asparagine
P	Pro	Proline
Q	Gln	Glutamine
R	Arg	Arginine
S	Ser	Serine
T	Thr	Threonine
V	Val	Valine
W	Trp	Tryptophan
Y	Tyr	Tyrosine

Brief contents

Contents