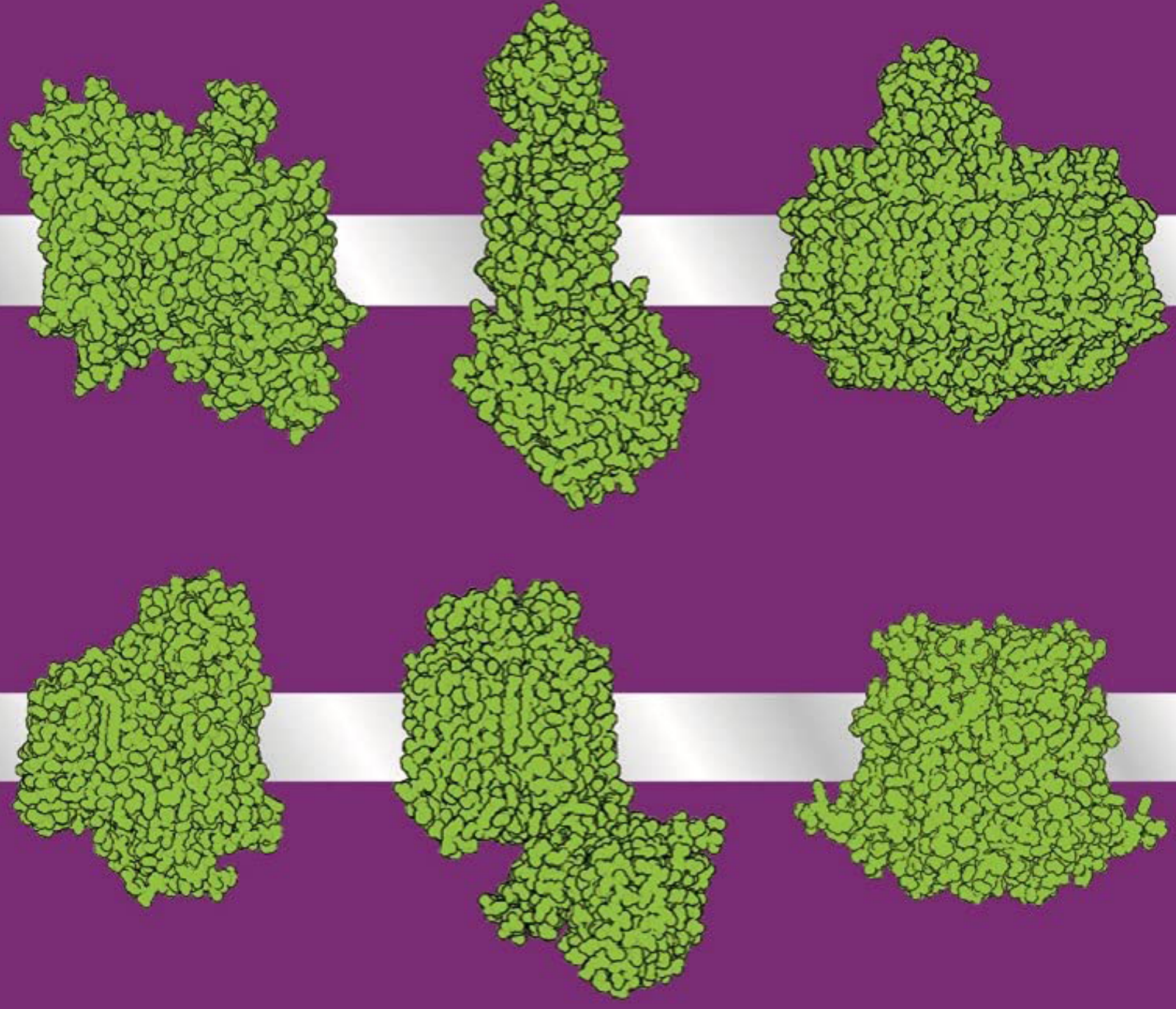
MOLECULAR BIOLOGY OF THE CELL

SEVENTH EDITION



ALBERTS HEALD JOHNSON MORGAN RAFF ROBERTS WALTER

Molecular Biology of THE CELL

Seventh Edition

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Bruce Alberts

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With problems by

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Preface

Why a cell biology textbook? What is its value in a world of online resources so vast that any information you might want about cells is, in principle, freely available a few taps away?

The answer is that a textbook provides what open-ended Internet searches cannot—a curation of knowledge and an expert, accurate guide to the beauty and complexities of cells. Our book provides a narrative that leads the reader logically and progressively through the key concepts, components, and experiments in such a way that readers can build for themselves a memorable, conceptual framework for cell biology—a framework that will allow them to understand and critically evaluate the exciting rush of new discoveries. That is what we have tried to do in *Molecular Biology of the Cell* for each of its seven editions.

This edition was completed during the COVID-19 pandemic. Many of the questions that this global crisis generated are cell biological questions—including how the virus gets into our cells, how it replicates, how our immune system responds, how vaccines are developed, and how scientists produce the molecular details of virus structure. Required for the rapid development of safe and effective COVID-19 vaccines, answers to all of these questions can be found in this textbook. To make room for them, as well as for many other major recent advances in our knowledge, much previous content had to be removed.

Understanding the inner workings of cells requires more than words. Our book contains more than 1500 illustrations that create a parallel narrative, closely interwoven with the text. Each figure has been designed to highlight a key concept. The unique clarity, simplicity, and consistency of the figures across chapters, achieved by use of a common set of icon designs and colors (for example, DNA *red* and proteins *green*), enables students to scan them as chapter overviews. In this edition, important protein structures are depicted and their Protein Data Bank (PDB) codes provided; these codes link to tools on the RCSB PDB website (www.rcsb.org), where students can more fully explore the proteins that lie at the core of cell biology. In addition, more than 180 narrated movies have been produced for the book, each linked to the text to provide additional insights.

John Wilson and Tim Hunt have again contributed their distinctive and imaginative problems to help students gain a more active understanding of the text. The end-of-chapter problems emphasize experiments and quantitative approaches in order to encourage critical thinking. Their Digital Problems Book in Smartwork greatly expands on these self-assessment problems and includes data analysis and video review questions that are based on the movie links in the textbook.

Many millions of scientific papers are relevant to cell biology, and many important new ones are published daily. The challenge for textbook writers is to sort through this overwhelming wealth of information to produce a clear and accurate conceptual platform for understanding how cells work. We have aimed high, seeking primarily to support the education of cell biology students, including the next generation of bioscientists, but also to support active scientists pursuing new fundamental research and the search for practical advances to improve the human condition.

So, why read a textbook? We live in a world that presents humanity with many challenging problems related to cell biology, including declining biodiversity, climate change, food insecurity, environmental degradation, resource depletion, and animal and plant diseases. We hope that this new edition of our textbook will help the reader to better understand these problems and—for many—to contribute to solving them.

Note to the Reader

What's New in the Seventh Edition?

Every chapter in the Seventh Edition has been significantly updated with information on new discoveries in the field of cell biology. Examples of this new content include:

- Updated information on the continuing impact of human genome research, including what has been learned from sequencing hundreds of thousands of human genomes (Chapter 4), and updated coverage of tumor genomes (Chapter 20).
- New research on pathogens, diseases, and methods of combating them, including discussion of COVID-19 (Chapters 1, 5, and 23) and mRNA vaccines (Chapter 24).
- Updated research on cellular organization, including new information on biomolecular condensates (Chapters 3, 6, 7, 12, and 14) and on chromosome organization by DNA loop extrusion (Chapters 4, 7, and 17).
- Expanded coverage of new microscope technologies, including superresolution light microscopy and atomic resolution electron microscopy (Chapter 9), and new research breakthroughs from cryo-electron microscopy, such as stretch-activated Piezo channels (Chapter 11).
- New coverage of evolution, including a new discussion on the diversity of life (Chapter 1), plus updates on both human (Chapter 4) and HIV (Chapter 23) evolution.

In addition, a quarter of the book's illustrations are either completely new or significantly updated for accuracy, clarity, and visual appeal.

Finally, we are thrilled to offer online assessment, for the first time, with the Digital Problems Book in Smartwork—reimagining the classic companion text, *The Problems Book*, for twenty-first century instructors and students.

Structure of the Book

Although the chapters of this book can be read independently of one another, they are arranged in a logical sequence of five parts. The first three chapters of Part I cover elementary principles and basic biochemistry. They can serve either as an introduction for those who have not studied biochemistry or as a refresher course for those who have. Part II deals with the storage, expression, and transmission of genetic information. Part III presents the principles of the main experimental methods for investigating and analyzing cells; here, a section titled "Mathematical Analysis of Cell Function" in Chapter 8 provides an extra dimension in our understanding of cell regulation and function. Part IV describes the internal organization of the cell. Part V follows the behavior of cells in multicellular systems, starting with how cells become attached to each other and concluding with chapters on pathogens and infection and on the innate and adaptive immune systems.

End-of-Chapter Problems

A selection of problems, written by John Wilson and Tim Hunt, appears in the text at the end of each chapter. Solutions to these problems are available on the Norton Teaching Tools site.

References

A concise list of selected references is included at the end of each chapter. These are arranged in alphabetical order by author surname under the main chapter section headings. These references often include the original papers in which the most critical discoveries were first reported. The ebook also includes the DOI identifier for the references, making it easy for students to access the articles.

Glossary Terms

Throughout the book, boldface type has been used to highlight key terms at the point in a chapter where the main discussion occurs. Italic type is used to set off important terms with a lesser degree of emphasis. At the end of the book is an expanded glossary, covering all the major terms common to cell biology; it should be the first resort for a reader who encounters an unfamiliar technical word.

Website for Students

Resources for students are available at **digital.wwnorton.com/mboc7**. The complete glossary as well as a set of flashcards are available on this student website.

Nomenclature for Genes and Proteins

Each species has its own conventions for naming genes; the only common feature is that they are always set in italics. In some species (such as humans), gene names are spelled out all in capital letters; in other species (such as zebrafish), all in lowercase; in yet others (most mouse genes), with the first letter in uppercase and the rest in lowercase; or (as in *Drosophila*) with different combinations of uppercase and lowercase, according to whether the first mutant allele to be discovered produced a dominant or recessive phenotype. Conventions for naming protein products are equally varied.

This typographical chaos drives everyone crazy. Moreover, there are many occasions, especially in a book such as this, where we need to refer to a gene generically—without specifying the mouse version, the human version, the chick version, or the hippopotamus version—because the gene variants across species are all equivalent for the purposes of our discussion. What convention then should we use?

We have decided in this book to follow a uniform rule. We write all gene names with the first letter in uppercase and the rest in lowercase, and all in italics, thus: *Bazooka*, *Cdc2*, *Dishevelled*, *Egl1*. The corresponding protein, where it is named after the gene, will be written in the same way, but in roman rather than italic letters: Bazooka, Cdc2, Dishevelled, Egl1. When it is necessary to specify the organism, this can be done with a prefix to the gene name.

For completeness, we list a few further details of naming rules that we shall follow. In some instances, an added letter in the gene name is traditionally used to distinguish between genes that are related by function or evolution; for those genes, we put that letter in uppercase if it is usual to do so (*LacZ*, *RecA*, *HoxA4*). Proteins are more of a problem. Many of them have names in their own right, assigned to them before the gene was named. Such protein names take many forms, although most of them traditionally begin with a lowercase letter (actin, hemoglobin, catalase); others are acronyms (such as GFP, for green fluorescent protein, or BMP4, for bone morphogenetic protein 4). To force all such protein names into a uniform style would do too much violence to established usages, and we shall simply write them in the traditional way. For the corresponding gene names in all these cases, we shall nevertheless follow our standard rule: *Actin*, *Hemoglobin*, *Catalase*, *Bmp4*, *Gfp*.

For those who wish to know them, the table shows some of the official conventions for individual species—conventions that we shall mostly violate in this book, in the manner shown.

Organism	Species-specific convention		Unified convention used in this book	
	Gene	Protein	Gene	Protein
Mouse	*Hoxa4*	Hoxa4	*HoxA4*	HoxA4
	Bmp4	BMP4	*Bmp4*	BMP4
	integrin α-1, Itgα1	integrin α1	*Integrin α1, Itgα1*	integrin α1
Human	*HOXA4*	HOXA4	*HoxA4*	HoxA4
Zebrafish	*cyclops, cyc*	Cyclops, Cyc	*Cyclops, Cyc*	Cyclops, Cyc
Caenorhabditis	*unc-6*	UNC-6	*Unc6*	Unc6
Drosophila	*sevenless, sev* (named after recessive phenotype)	Sevenless, SEV	*Sevenless, Sev*	Sevenless, Sev
	Deformed, Dfd (named after dominant mutant phenotype)	Deformed, DFD	*Deformed, Dfd*	Deformed, Dfd
Yeast				
Saccharomyces cerevisiae (budding yeast)	*CDC28*	Cdc28, Cdc28p	*Cdc28*	Cdc28
Schizosaccharomyces pombe (fission yeast)	*Cdc2*	Cdc2, Cdc2p	*Cdc2*	Cdc2
Arabidopsis	*GAI*	GAI	*Gai*	GAI
Escherichia coli	*uvrA*	UvrA	*UvrA*	UvrA

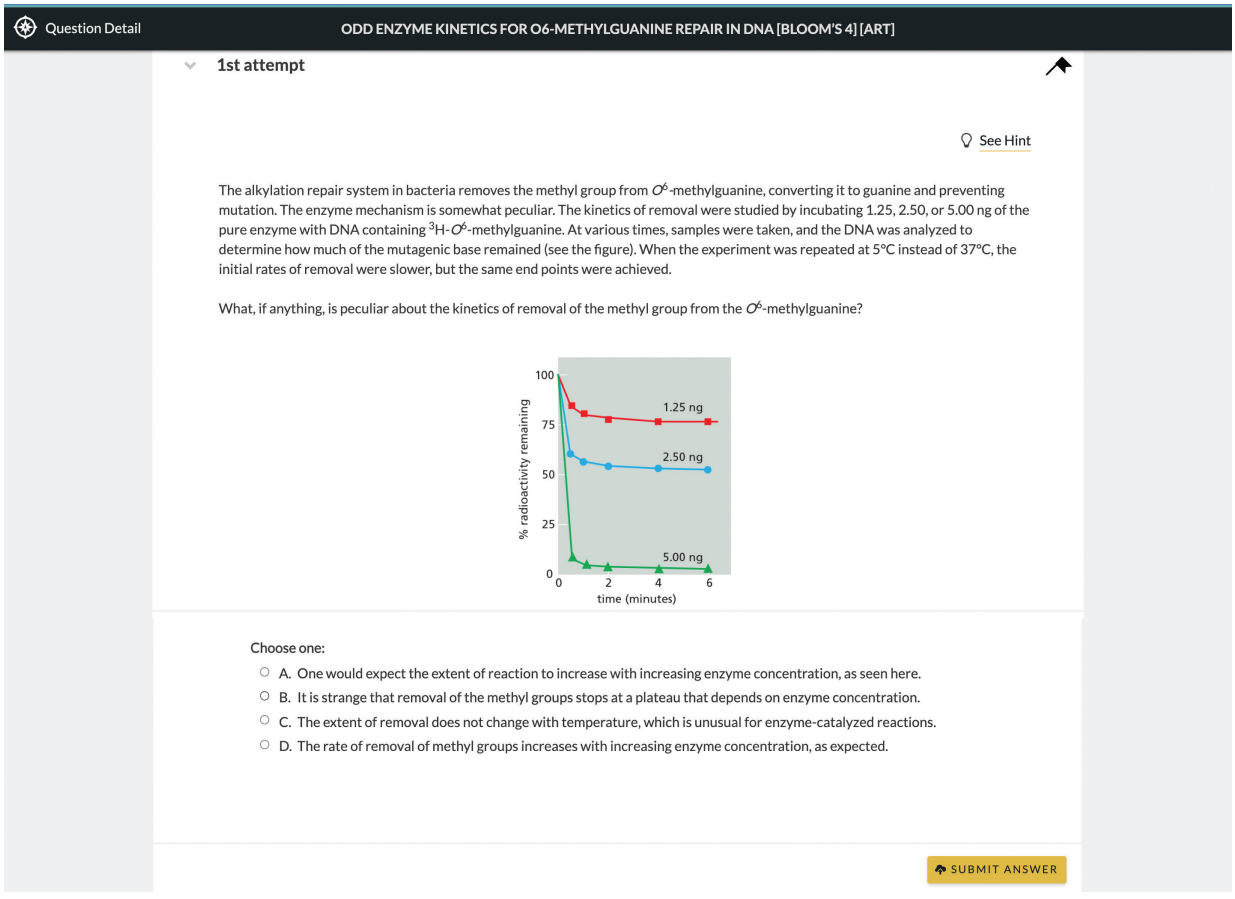
Resources for Instructors

digital.wwnorton.com/mboc7

Designed to enrich the classroom experience, Instructor Resources are available at **digital.wwnorton.com/mboc7**. Adopting instructors can obtain access to the site from their sales representative, who can be identified by visiting wwnorton .com/educator and clicking the "Find My Rep" button.

The Digital Problems Book in Smartwork

For the first time, the popular print supplement *Molecular Biology of the Cell: The Problems Book* is now available in Smartwork. Easier for instructors to assign and more helpful to students because of each question's pedagogical scaffolding, the Digital Problems Book in Smartwork features the questions authored by Tim Hunt and John Wilson adapted for digital delivery. An enormous library of almost 3500 questions that include critical thinking questions, data analysis questions, and animation and video questions, allows instructors to deliver the exact type of assessment that their students need. The Digital Problems Book in Smartwork comes at no additional cost with all new copies of *Molecular Biology of the Cell*.



Norton Teaching Tools

The Norton Teaching Tools site for *Molecular Biology of the Cell* provides creative and engaging resources to refresh a syllabus or to design a new one. Dynamic, experienced instructors have created primary literature suggestions, active learning activities, lecture PowerPoint files, descriptions of all of the animations and videos, and much more. All of the teaching tools are aligned with chapter topics and organized by activity type, making it easily sortable. The site also features tips for assigning Norton's digital learning tools and addressing the most common course challenges.

Animations and Videos

Under the authorial direction of Michele M. McDonough and Thomas A. Volpe, both of Northwestern University, the animations and video library has been thoroughly updated and expanded. The more than 180 animations and videos are integrated into the ebook and also available to students and instructors at digital .wwnorton.com/mboc7. Instructors can view descriptions of each on the Norton Teaching Tools site.

Norton Ebook

The purchase of any new print copy of the Seventh Edition of *Molecular Biology of the Cell* includes access to the Norton Ebook version of the text at no additional cost. The Norton Ebook can be purchased as an affordable stand-alone option that provides an active reading experience, enabling students to take notes, bookmark, search, highlight, and read offline. All of the videos and animations appear directly in the ebook, and instructors can add notes that students can see as they are reading the text.

Art of *Molecular Biology of the Cell*, Seventh Edition

The images from the book are available in two convenient formats: PowerPoint and JPEG, and in both labeled and unlabeled versions.

Figure-integrated Lecture Outlines

The section headings, concept headings, and figures from the text have been integrated into PowerPoint presentations and can be customized. For example, the content of these presentations can be combined with videos, questions from the book, or activities in the Norton Teaching Tools site, in order to create unique lectures that facilitate interactive learning.

Test Bank

Updated for the Seventh Edition, the test bank includes a variety of question formats: multiple choice, short answer, fill-in-the-blank, true–false, and matching. The test bank was created with the philosophy that a good exam should require students to reflect upon and integrate information as a part of a sound understanding. Questions are classified by section and difficulty, making it easy to construct tests and quizzes. The test bank question library includes about 70 questions per chapter, ensuring instructors can find the right questions for their exams. It will be delivered through Norton Testmaker, which brings the high-quality questions in the test bank online. Create assessments for your course without downloading files or installing specialized software, customize test bank questions, and easily export your tests to Microsoft Word or Common Cartridge files for your learning management system (LMS).

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INTRODUCTION TO THE CELL

CHAPTER 1

Cells, Genomes, and the Diversity of Life

The surface of our planet is populated by living things—*organisms*—curious, intricately organized chemical factories that take in matter from their surroundings and use these raw materials to generate copies of themselves. These organisms appear extraordinarily diverse. What could be more different than a tiger and a piece of seaweed or a butterfly and a tree? Yet our ancestors, knowing nothing of cells or DNA, saw that all these things had something in common. They called that something "life," marveled at it, struggled to define it, and despaired of explaining what it was or how it worked in terms that relate to nonliving matter.

The remarkable discoveries of the past 100 years or so have not diminished the marvel—quite the contrary. But they have removed the central mystery regarding the nature of life. We can now see that all living things are made of cells: small, membrane-enclosed units filled with a concentrated aqueous solution of chemicals and endowed with the extraordinary ability to create copies of themselves by growing and then dividing in two.

Because cells are the fundamental units of life, it is to *cell biology*—the study of the structure, function, and behavior of cells—that we must look for answers to the questions of what life is and how it works. With a deeper understanding of cells and their evolution, we can begin to tackle the grand historical problems of life on Earth: its mysterious origins, its stunning diversity, and its invasion of every conceivable habitat. Indeed, as emphasized long ago by the pioneering cell biologist E. B. Wilson, "the key to every biological problem must finally be sought in the cell; for every living organism is, or at some time has been, a cell."

Despite their apparent diversity, living things are fundamentally similar inside. The whole of biology is thus a counterpoint between two themes: astonishing variety in individual particulars and astonishing constancy in fundamental mechanisms. In this chapter, we begin by outlining the universal features common to all life on our planet, along with some of the fundamental properties of their cells. We then discuss how an analysis of DNA *genomes* allows scientists to position the wide variety of organisms in an evolutionary "tree of life." This

IN THIS CHAPTER