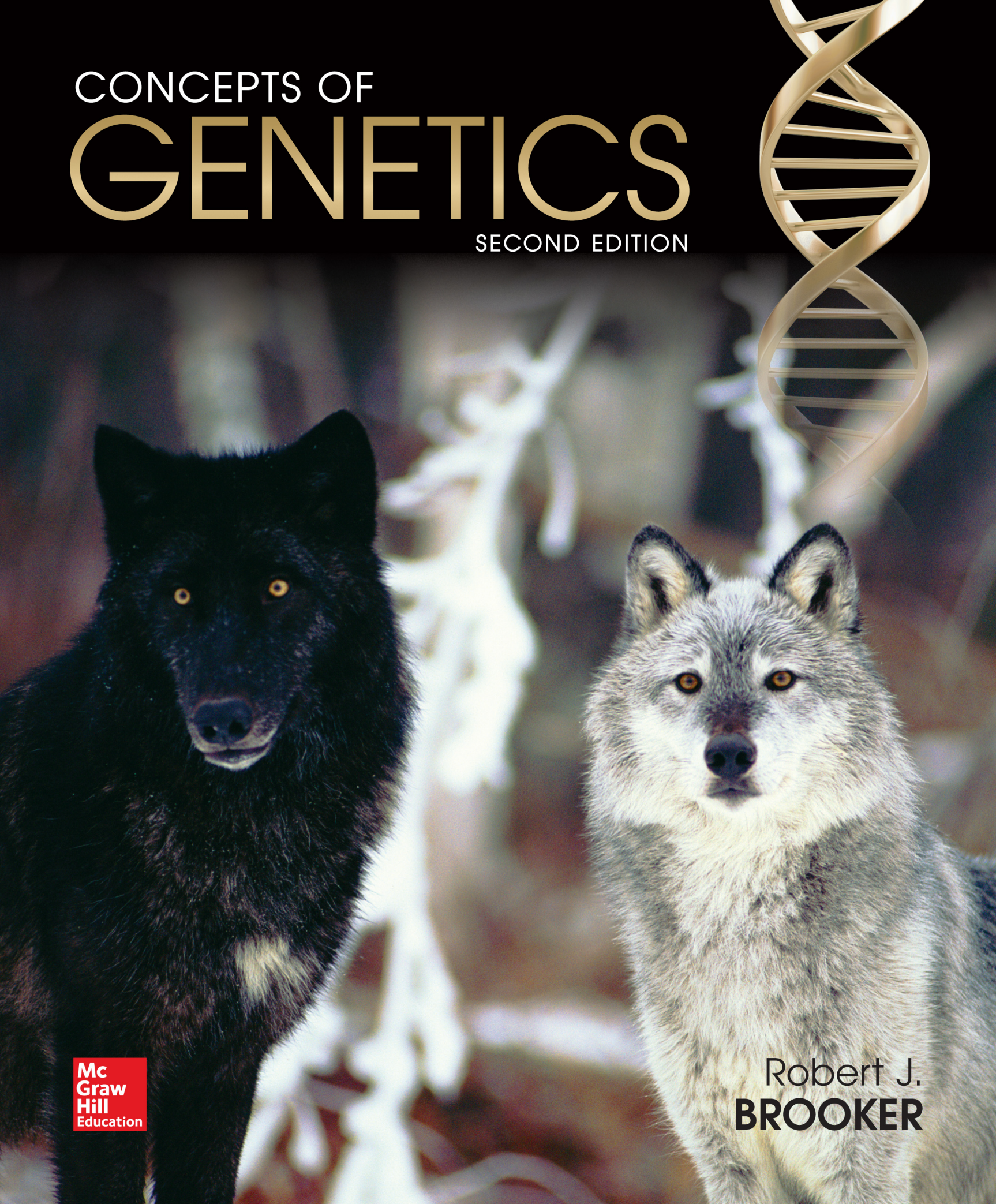
CONCEPTS OF GENETICS

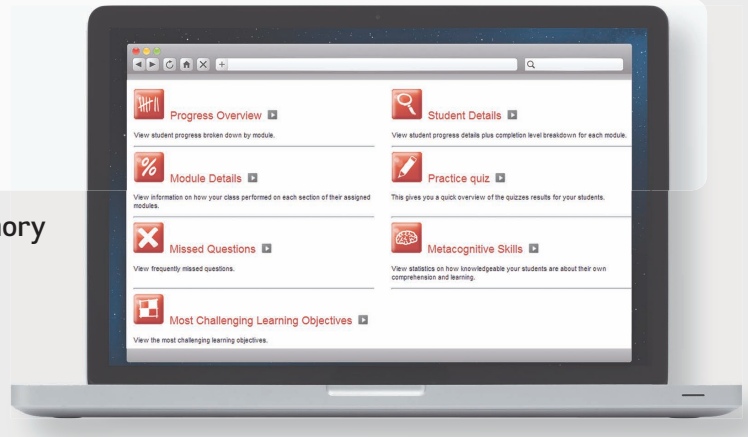
SECOND EDITION



Robert J. BROOKER

Mc Graw Hill Education

LEARNSMART®



The market leading adaptive study tool proven to strengthen memory recall, increase class retention and boost grades.

- Moves students beyond memorizing
- Allows instructors to align content with their goals
- Allows instructors to spend more time teaching higher level concepts

SMARTBOOK®

The first—and only—adaptive reading experience designed to transform the way students read.

- Engages students with a personalized reading experience
- Ensures students retain knowledge

LEARNSMART PREP®

An adaptive course preparation tool that quickly and efficiently helps students prepare for college level work.

- Levels out student knowledge
- Keeps students on track

LEARNSMART ACHIEVE®

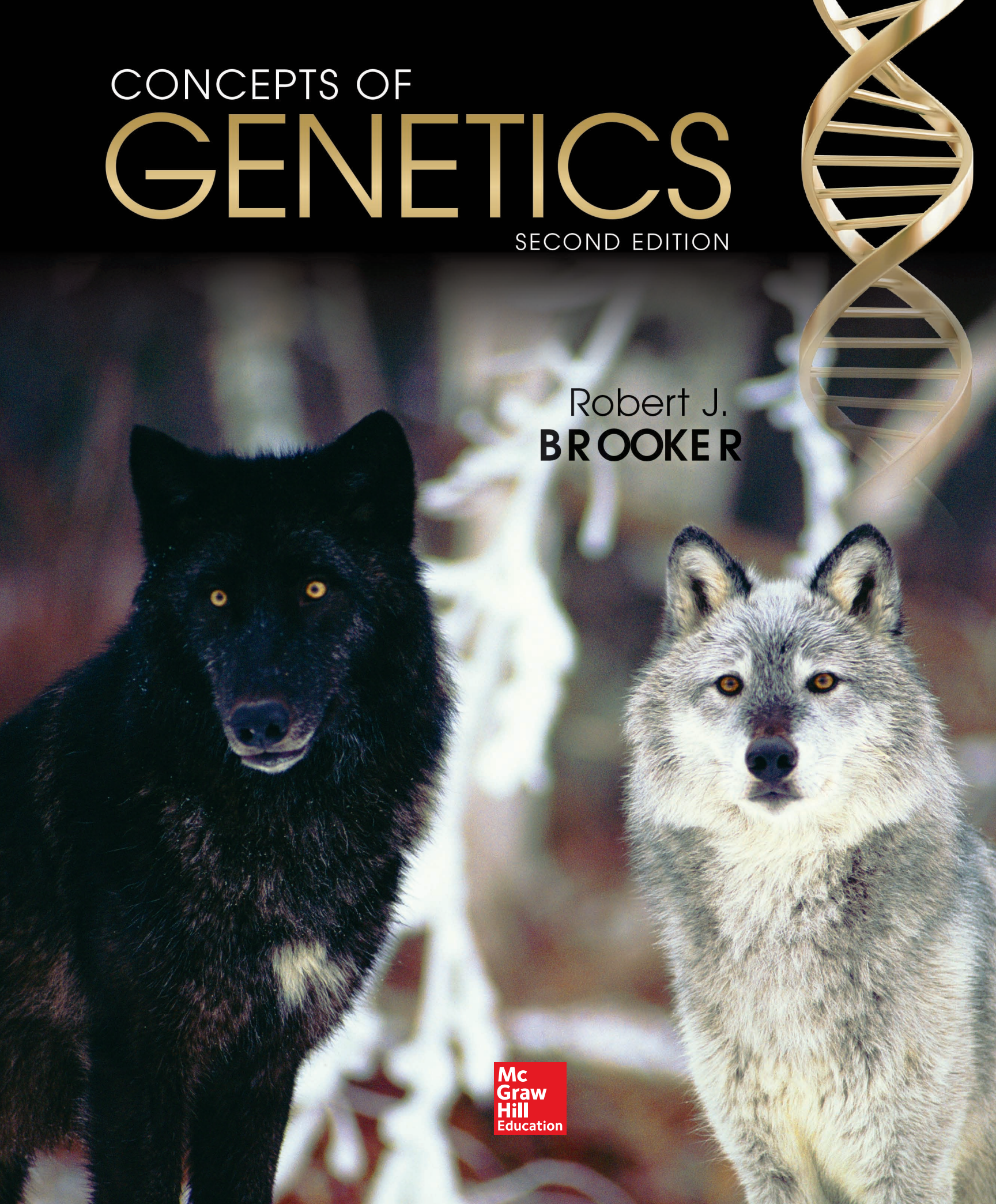
A learning system that continually adapts and provides learning tools to teach students the concepts they don't know.

- Adaptively provides learning resources
- A time management feature ensures students master course material to complete their assignments by the due date

WWW.LEARNSMARTADVANTAGE.COM

CONCEPTS OF GENETICS

SECOND EDITION



Robert J. BROOKER

Mc Graw Hill Education

CONCEPTS OF GENETICS, SECOND EDITION

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 0 RMN/RMN 1 0 9 8 7 6 5

ISBN 978-0-07-352535-8
MHID 0-07-352535-9

Senior Vice President, Products & Markets: *Kurt L. Strand*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Design & Delivery: *Kimberly Meriwether David*
Managing Director: *Michael Hackett*
Brand Manager: *Rebecca Olson*
Director, Product Development: *Rose Koos*
Marketing Manager: *Patrick Reidy*
Director of Development: *Elizabeth Sievers*
Digital Product Analyst: *Jake Theobald*
Director, Content Design & Delivery: *Linda Avenarius*
Program Manager: *Angela R. FitzPatrick*
Content Project Managers: *Jayne Klein/Sherry L. Kane*
Buyer: *Sandy Ludovissy*
Designer: *David W. Hash*
Content Licensing Specialists: *John Leland/Lenny Behnke*
Cover Image: ©*Tom Vezo/naturepl.com*
Compositor: *Laserwords Private Limited*
Typeface: *10/12 Times LT Std*
Printer: *R. R. Donnelley*

Library of Congress Cataloging-in-Publication Data

Brooker, Robert J., author.
Concepts of genetics / Robert J. Brooker. -- Second edition.
pages cm
ISBN 978-0-07-352535-8 (acid-free paper)
1. Genetics. I. Title.
QH430.B764 2016
576.5—dc23

2014041472

ABOUT THE AUTHOR

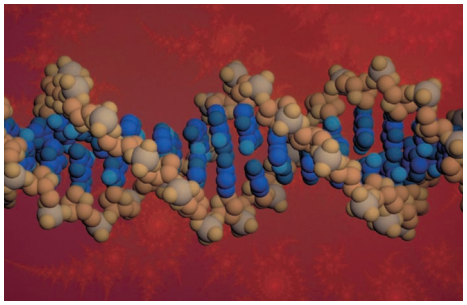
Robert J. Brooker is a professor in the Department of Genetics, Cell Biology, and Development and the Department of Biology Teaching and Learning at the University of Minnesota–Minneapolis. He received his B.A. in biology from Wittenberg University in 1978 and his Ph.D. in genetics from Yale University in 1983. At Harvard, he conducted postdoctoral studies on the lactose permease, which is the product of the *lacY* gene of the *lac* operon. He continues his work on transporters at the University of Minnesota. Dr. Brooker's laboratory primarily investigates the structure, function, and regulation of manganese and iron transporters found in bacteria and *C. elegans*. At the University of Minnesota he teaches undergraduate courses in biology, genetics, and cell biology.

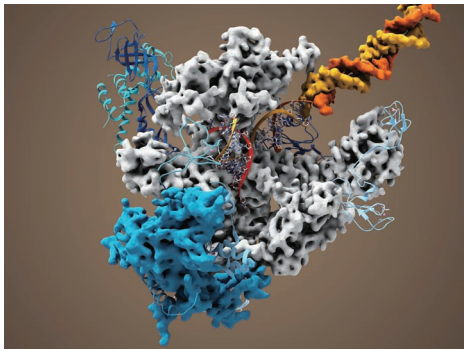
DEDICATION

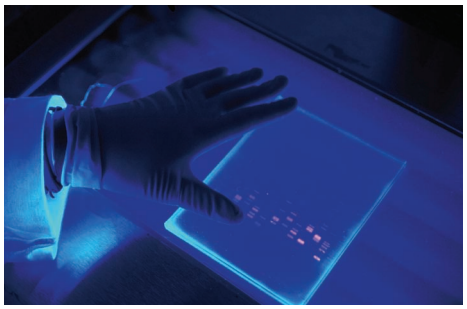
To my wife, Deborah, and our children,
Daniel, Nathan, and Sarah

BRIEF CONTENTS

TABLE OF CONTENTS







PREFACE

Based on our discussions with instructors from many institutions, I have learned that most instructors want a broad textbook that clearly explains concepts in a way that is interesting, accurate, concise, and up-to-date. *Concepts of Genetics* has been written to achieve these goals. It is intended for students who want to gain a conceptual grasp of the various fields of genetics. The content reflects current trends in genetics, and the pedagogy is based on educational research. In particular, a large amount of formative assessment is woven into the content. As an author, researcher, and teacher, I want a textbook that gets students actively involved in learning genetics. To achieve this goal, I have worked with a talented team of editors, illustrators, and media specialists who have helped me to make the second edition of *Concepts of Genetics* a fun learning tool.

FLIPPING THE CLASSROOM

A relatively recent trend in science education is the phenomenon that is sometimes called "flipping the classroom." This phrase refers to the idea that some of the activities that used to be done in class are now done out of class, and vice versa. For example, instead of spending the entire class time lecturing over textbook and other materials, some of the class time is spent engaging students in various activities, such as problem solving, working through case studies, and designing experiments. This approach is called active learning. For many instructors, the classroom has become more learner centered rather than teacher centered. A learner-centered classroom provides a rich environment in which students can interact with each other and with their instructors. Instructors and fellow students often provide formative assessment—immediate feedback that helps students understand if their learning is on the right track.

What are some advantages of active learning? Educational studies reveal that active learning usually promotes greater learning gains. In addition, active learning often focuses on skill development rather than the memorization of facts that are easily forgotten. Students become trained to "think like scientists" and to develop a skill set that enables them to apply scientific reasoning. A common concern among instructors who are beginning to try out active learning is that they think they will have to teach their students less material. However, this may not be the case. Although students may be provided with online lectures, "flipping the classroom" typically gives students more responsibility for understanding the textbook material on their own. Along these lines, *Concepts of Genetics,* Second Edition, is intended to provide students with a resource that can be effectively used out of the classroom. Several key pedagogical features include the following:

- ***NEW!* Learning Outcomes** Each section of every chapter begins with a set of learning outcomes. These outcomes help students understand what they should be able to do if they have mastered the material in that section.
- **Formative Assessment** When students are expected to learn textbook material on their own, it is imperative that they are given formative assessment on a regular basis so they can gauge whether or not they are mastering the material. Formative assessment is a major feature of this textbook and is bolstered by McGraw-Hill Connect®—a state-of-the art digital assignment and assessment platform. In *Concepts of Genetics,* Second Edition, formative assessment is provided in multiple ways.
  1. Each section of every chapter ends with multiple choice questions. Also, compared to the 1st edition, many chapters in the second edition are divided into more sections, which are shorter in length. Formative assessment at the end of each section allows students to evaluate their mastery of the material before moving on to the next section.
  2. Most figures have concept check questions so students can determine if they understand the key points in the figure.
  3. Extensive end-of chapter questions continue to provide students with feedback regarding their mastery of the material.
  4. ***NEW!*** A new feature called ***Genetic TIPS*** provides a consistent approach to help students solve problems in genetics. This approach has three components. First, the student is made aware of the ***T***opic at hand. Second, the question is evaluated with regard to the ***I***nformation that is available to the student. Finally, the student is guided through a ***P***roblem-*S*olving ***S***trategy to tackle the question.
  5. Additional questions, including questions that pertain to every feature investigation, are available to the student in Connect: http://successinhighered.com/genetics-molecular-biology
  6. The textbook material is supported by digital learning tools found in Connect. Questions and activities are assignable in Connect. Assignments due before class-time or following an in-class activity help students prepare or review.
  7. ***NEW!*** McGraw-Hill LearnSmart and SmartBook are adaptive learning tools available in Connect that have been proven to strengthen recall and increase retention so that students can move beyond memorizing and truly learn the material.

- **Chapter Organization** In genetics, it is sometimes easy to "lose the forest for the trees." Genetics is oftentimes a dense subject. To circumvent this difficulty, the content in *Concepts of Genetics* has been organized to foster a better appreciation for the big picture of genetic principles. The chapters are divided into several sections, and each section ends with a summary that touches on the main points. As mentioned, multiple choice questions at the end of each section are also intended to help students grasp the broader concepts in genetics. Finally, the end of each chapter contains a summary, which allows students to connect the concepts that were learned in each section.
- **Interactive Exercises** Working with education specialists, the author has crafted interactive exercises in which the students can make their own choices in problem-solving activities and predict what the outcomes will be. Many of these exercises are focused on inheritance patterns and human genetic diseases. (For example, see Chapters 5 and 24.) In addition, we have many interactive exercises for the molecular chapters. These types of exercises engage students in the learning process. The interactive exercises are found online, and the corresponding material in the chapter is indicated with an Interactive Exercise icon.

- **Animations** Our media specialists have created over 50 animations for a variety of genetic processes. These animations were made specifically for this textbook and use the art from the textbook. The animations literally make many of the figures in the textbook "come to life." The animations are found online and the corresponding material in the chapter is indicated with an Online Animation icon.

An effective textbook needs to accomplish three goals. First, it needs to provide comprehensive, accurate, and up-to-date content in its field. Second, it needs to expose students to the techniques and skills they will need to become successful in that field. And finally, it should inspire students so they want to study the material. The hard work that has gone into the second edition of *Concepts of Genetics* has been aimed at achieving all three of these goals. Furthermore, the pedagogy of *Concepts of Genetics* has been designed to foster student learning. Instead of being a collection of "facts and figures," *Concepts of Genetics,* Second Edition, by Robert Brooker, is intended to be an engaging and motivating textbook in which formative assessment allows students to move ahead and learn the material in a productive way. We welcome your feedback so we can make future editions even better!

HOW WE EVALUATED YOUR NEEDS

ORGANIZATION

In surveying many genetics instructors, it became apparent that most people fall into two camps: **Mendel first** versus **Molecular first**. I have taught genetics both ways. As a teaching tool, this textbook has been written with these different teaching strategies in mind. The organization and content lend themselves to various teaching formats.

Chapters 2 through 10 are largely inheritance chapters, whereas Chapters 25 and 26 examine population and quantitative genetics. The bulk of the molecular genetics is found in Chapters 11 through 24, although I have tried to weave a fair amount of molecular genetics into Chapters 2 through 10 as well. The information in Chapters 11 through 24 does not assume that a student has already covered Chapters 2 through 10. Actually, each chapter is written with the perspective that instructors may want to vary the order of their chapters to fit their students' needs.

For those who like to discuss inheritance patterns first, a common strategy would be to cover Chapters 1 through 10 first, and then possibly 25 and 26. (However, many instructors like to cover quantitative and population genetics at the end. Either way works fine.) The more molecular and technical aspects of genetics would then be covered in Chapters 11 through 24. Alternatively, if you like the "Molecular first" approach, you would probably cover Chapter 1, then skip to Chapters 11 through 24, then return to Chapters 2 through 10, and then cover Chapters 25 and 26 at the end of the course. This textbook was written in such a way that either strategy works well.

ACCURACY

Both the publisher and I acknowledge that inaccuracies can be a source of frustration for both the instructor and students. Therefore, throughout the writing and production of this textbook we have worked very hard to catch and correct errors during each phase of development and production.

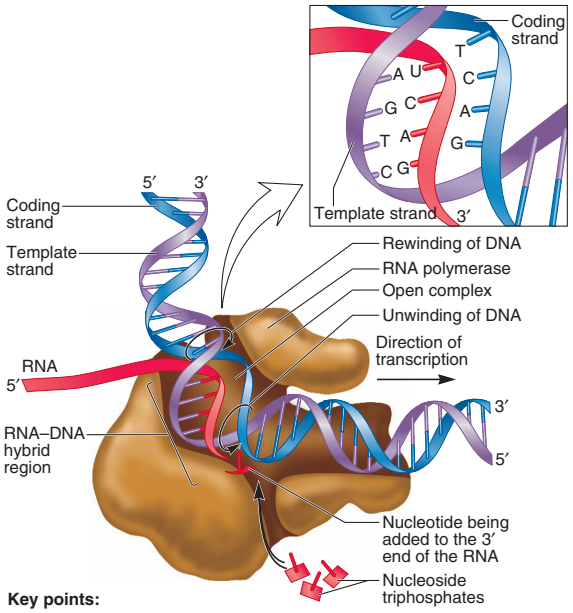
Each chapter has been reviewed by faculty members who teach the course or conduct research in genetics or both. In addition, a developmental editor has gone through the material to check for accuracy in art and consistency between the text and art. When they were first developed, we had a team of students work through all of the problem sets and one developmental editor also checked them. The author personally checked every question and answer when the chapters were completed for this edition.

ILLUSTRATIONS

In surveying students whom I teach, I often hear it said that most of their learning comes from studying the figures. Likewise, instructors frequently use the illustrations from a textbook as a central teaching tool. For these reasons, a great amount of effort has gone into the illustrations. The illustrations are created with four goals in mind:

1. **Completeness** For most figures, it should be possible to understand an experiment or genetic concept by looking at the illustration alone. Students have complained that it is difficult to understand the content of an illustration if they have to keep switching back and forth between the figure and text. In cases where an illustration shows the steps in a scientific process, the steps are described in brief statements that allow the students to understand the whole process (e.g., see Figure 17.10). Likewise, such illustrations should make it easier for instructors to explain these processes in the classroom.

2. **Clarity** The figures have been extensively reviewed by students and instructors. This has helped us to avoid drawing things that may be confusing or unclear. I hope that no one looks at an element in any figure and wonders, "What is that thing?" Aside from being unmistakably drawn, all new elements within each figure are clearly labeled.
3. **Consistency** Before we began to draw the figures, we generated a style sheet that contained recurring elements that are found in many places in the textbook. Examples include the DNA double helix, DNA polymerase, and fruit flies. We agreed on the best way(s) to draw these elements and also what colors they should be. Therefore, as students and instructors progress through this textbook, they become accustomed to the way things should look.
4. **Realism** An important emphasis of this textbook is to make each figure as realistic as possible. When drawing macroscopic elements (e.g., fruit flies, pea plants), the illustrations are based on real images, not on cartoonlike simplifications. Our most challenging goal, and one that we feel has been achieved most successfully, is the realism of our molecular drawings. Whenever possible, we have tried to depict molecular elements according to their actual structures, if such structures are known. For example, the ways we have drawn RNA polymerase, DNA polymerase, DNA helicase, and ribosomes are based on their crystal structures. When a student sees a figure in this textbook that illustrates an event in transcription, RNA polymerase is depicted in a way that is as realistic as possible (e.g., Figure 14.8 below).



Key points:

- RNA polymerase slides along the DNA, creating an open complex as it moves.
- The DNA strand known as the template strand is used to make a complementary copy of RNA, resulting in an RNA–DNA hybrid.
- RNA polymerase moves along the template strand in a 3′ to 5′ direction, and RNA is synthesized in a 5′ to 3′ direction using nucleoside triphosphates as precursors. Pyrophosphate is released (not shown).
- The complementarity rule is the same as the AT/GC rule except that U is substituted for T in the RNA.

FEATURE EXPERIMENTS

Many chapters have one or two experiments that are presented according to the scientific method. These experiments are integrated within the chapters and flow with the rest of the text. As you are reading the experiments, you will simultaneously explore the scientific method and the genetic principles that have been discovered using this approach. For students, I hope this textbook helps you to see the fundamental connection between scientific analysis and principles. For both students and instructors, I expect that this strategy makes genetics much more fun to explore.

WRITING STYLE

Motivation in learning often stems from enjoyment. If you enjoy what you're reading, you are more likely to spend longer amounts of time with it and focus your attention more crisply. The writing style of this book is meant to be interesting, down to earth, and easy to follow. Each section of every chapter begins with an overview of the contents of that section, usually with a table or figure that summarizes the broad points. The section then examines how those broad points were discovered experimentally, as well as explaining many of the finer scientific details. Important terms are introduced in a boldface font. These terms are also found at the end of the chapter and in the glossary.

There are various ways to make a genetics book interesting and inspiring. The subject matter itself is pretty amazing, so it's not difficult to build on that. In addition to describing the concepts and experiments in ways that motivate students, it is important to draw on examples that bring the concepts to life. In a genetics book, many of these examples come from the medical realm. This textbook contains lots of examples of human diseases that exemplify some of the underlying principles of genetics. Students often say they remember certain genetic concepts because they remember how defects in certain genes can cause disease. For example, defects in DNA repair genes cause a higher predisposition to develop cancer. In addition, I have tried to be evenhanded in providing examples from the microbial and plant world. Finally, students are often interested in applications of genetics that affect their everyday lives. Because we frequently hear about genetics in the news, it's inspiring for students to learn the underlying basis for such technologies. Chapters 20 to 23 are devoted to genetic technologies, and applications of these and other technologies are found throughout this textbook. By the end of their genetics course, students should come away with a greater appreciation for the influence of genetics in their lives.

SIGNIFICANT CONTENT CHANGES TO THE SECOND EDITION

- Each section of every chapter begins with learning outcomes and ends with multiple choice questions.
- As mentioned, a new feature called ***Genetic TIPS*** has been added within chapters and at the end of chapters to help students solve problems.

Examples of Specific Content Changes to Individual Chapters

- Chapter 1. Divided into a new section on the science of genetics; has an explanation of the new ***Genetic TIPS*** feature.
- Chapter 2. Chromosome Transmission during Cell Division and Sexual Reproduction: Improvement in the figures of mitosis and meiosis (see Figures 2.8 and 2.11).
- Chapter 3. Mendelian Inheritance: Divided into shorter sections that end in questions to help students gauge their understanding of Mendel's laws.
- Chapter 5. Extensions of Mendelian Inheritance: This revised chapter begins with an overview that compares different inheritance patterns, and then the inheritance patterns are placed in their own sections, which end with formative assessment questions. This approach should help students see the similarities and differences among the various patterns.
- Chapter 7. Genetic Linkage and Mapping in Eukaryotes: Contains a more concise presentation that focuses on plants and animals.
- Chapter 8. Variation in Chromosome Structure and Number: The 2nd edition contains a more streamlined presentation of Natural and Experimental Mechanisms That Produce Variation in Chromosome Number.
- Chapter 9. Genetics of Bacteria: Contains a new section on the medical relevance of bacterial gene transfer (Section 9.6).
- Chapter 10. Genetics of Viruses: Has a more concise presentation that focuses on viral structure, genetic composition, and reproductive cycles.
- Chapter 11. Molecular Structure of DNA and RNA: The four levels of DNA structure are introduced in an overview section and then the different levels of DNA structure are presented in their own sections, which are followed by formative assessment questions.
- Chapter 12. Molecular Structure and Organization of Chromosomes: Improvements have been made to several figures that depict chromatin structure (e.g., see Figure 12.15).
- Chapter 13. DNA Replication: The figure illustrating a three-dimensional view of DNA replication has been improved (see Figure 13.12).
- Chapter 14. Gene Transcription and RNA Modification: An improved figure has been added, which shows how sigma factor binds into the major groove (see Figure 14.6). A new section (Section 14.5) and summary table have been added at the end of the chapter that compares transcription and RNA modification between bacteria and eukaryotes.
- Chapter 15. Translation of mRNA: A new table has been added that describes how certain antibiotics inhibit translation (see Table 15.7).
- Chapter 17. Gene Regulation in Eukaryotes: Transcriptional Regulation. This chapter has a new section that focuses on epigenetic regulation (see Section 17.5).
- Chapter 18. Gene Mutation and DNA Repair: The figure concerning trinucleotide repeat expansion has been revised (see Figure 18.11).
- Chapter 19. Recombination, Immunogenetics, and Transposition: This is a new chapter that combines topics involving the breakage and rejoining of DNA segments. The figure concerning the function of transposase has been revised into a two-part figure, which shows how transposase causes the transposon to loop out (see Figure 19.10).
- Chapter 20. DNA Technologies: Based on reviewer feedback, the order of topics in this chapter has been revised. DNA sequencing and site-directed mutagenesis come directly after cloning methods.
- Chapter 21. Biotechnology: Various topics have been updated, such as the use of transgenic crops.
- Chapter 22. Genomics I: Analysis of DNA: A new section has been added on metagenomics (see Section 22.6).
- Chapter 23. Genomics II: Functional Genomics, Proteomics, and Bioinformatics: Includes updates to the topic of bioinformatics.
- Chapter 24. Medical Genetics and Cancer: This chapter ends with a new section on personalized medicine (see Section 24.6).
- Chapter 25. Population Genetics: The chapter now contains an overview of microevolution, and then natural selection, genetic drift, migration, nonrandom mating, and sources of new genetic variation are covered in their own separate sections.
- Chapter 26. Quantitative Genetics: This chapter in the 2nd edition presents a more streamlined view of how quantitative loci are mapped. A section on the general features of heritability precedes a section on selective breeding.

SUGGESTIONS WELCOME!

It seems very appropriate to use the word *evolution* to describe the continued development of this textbook. I welcome any and all comments. The refinement of any science textbook requires input from instructors and their students. These include comments regarding writing, illustrations, supplements, factual content, and topics that may need greater or less emphasis. You are invited to contact me at:

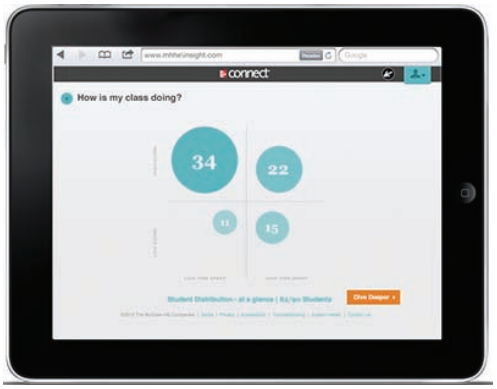
Dr. Rob Brooker
Dept. of Genetics, Cell Biology, and Development
University of Minnesota
6-160 Jackson Hall
321 Church St.
Minneapolis, MN 55455
brook005@umn.edu

TEACHING AND LEARNING RESOURCES

Help Your Students Prepare for Class

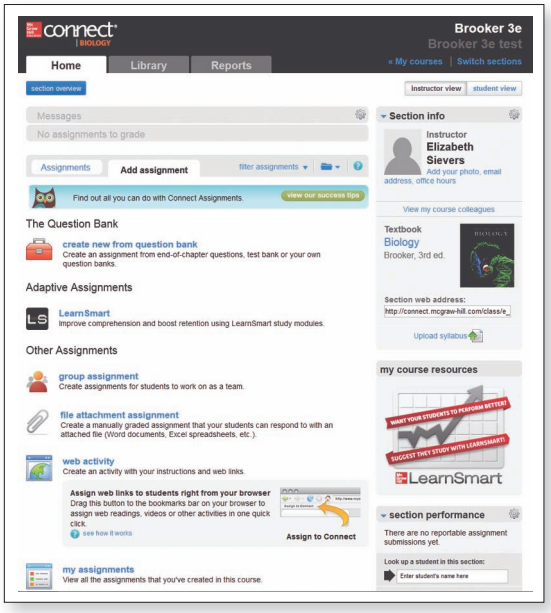
Digital resources can help you achieve your instructional goals—making your students more responsible for learning outside of class by meeting your students where they live: on the go and online. Use the text and digital tools to empower students to come to class more prepared and ready to engage!

McGraw-Hill Connect® Genetics provides online presentation, assignment, and assessment solutions. It connects your students with the tools and resources they'll need to achieve success. With **Connect Genetics** you can deliver assignments, quizzes, and tests online. A robust set of questions and activities is presented in the Question Bank and a separate set of questions to use for exams is presented in the Test Bank. Every question is tagged to a Learning Outcome and genetics topic so you can customize your assignments to the course material. As an instructor, you can edit existing questions and author entirely new problems. Track individual student performance—by question, by assignment, or in relation to the class overall—with detailed grade reports. Integrate grade reports easily with Learning Management Systems such as Blackboard and Canvas—and much more. **Connect Genetics** provides students with 24/7 online access to *Concepts of Genetics,* Second Edition *eBook*. This media-rich version of the book is available through the McGraw-Hill Connect and allows seamless integration of text, media, and assessments.



Connect® Insight is a powerful data analytics tool that allows instructors to leverage aggregated information about their courses and students to provide a more personalized teaching and learning experience.

To learn more, visit **www.mcgrawhillconnect.com**.

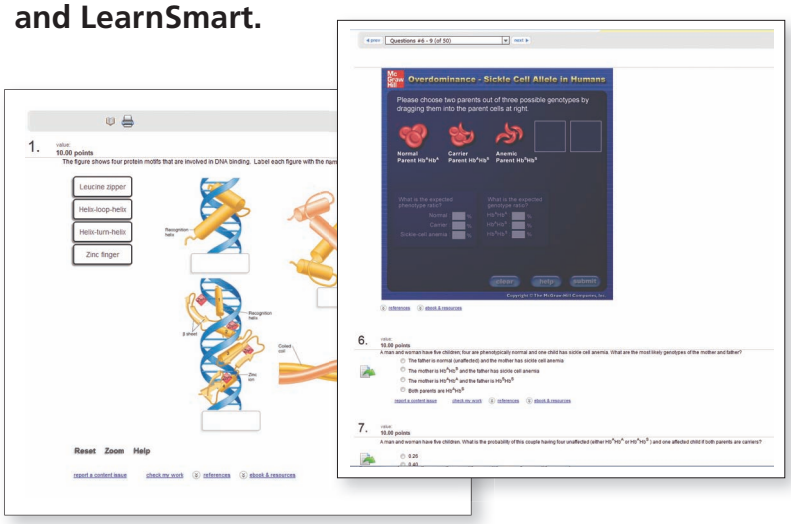


Assignments can include reading assignments from the eBook or SmartBook, homework or quizzes, LearnSmart and SmartBook, your own web or short answer activities, and more.

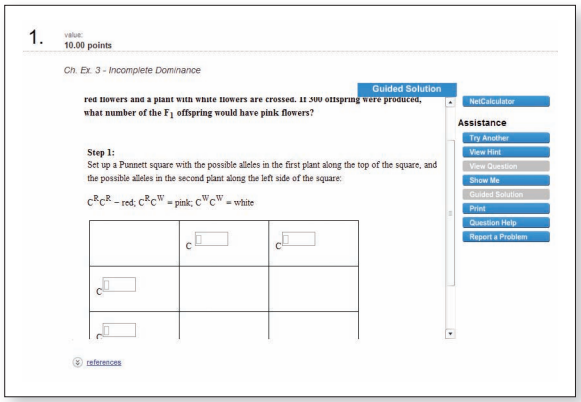
Help Your Students by Making Assignments—Reading, Homework, and LearnSmart

Connect content can be assigned as homework before class to help students with basic concepts so they can better understand classroom presentations and projects. Quizzes taken after class can also evaluate their comprehension. These assignments support the rich assessment presented in the text so that students and professors can gauge the level of understanding of concepts and the mastery of skills.

Help your students prepare for class and revisit content by assigning homework in Connect and LearnSmart.



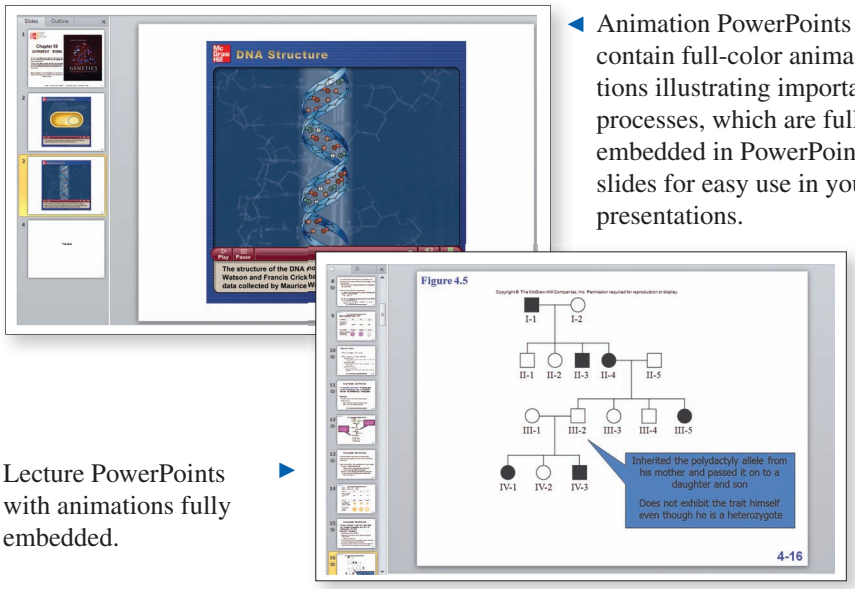
Interactive and traditional questions help assess your students' knowledge of the material. Having achieved a base level of knowledge, students will get more out of their time in class.



Quantitative questions help you challenge your students to apply material they learn in class and in the book.

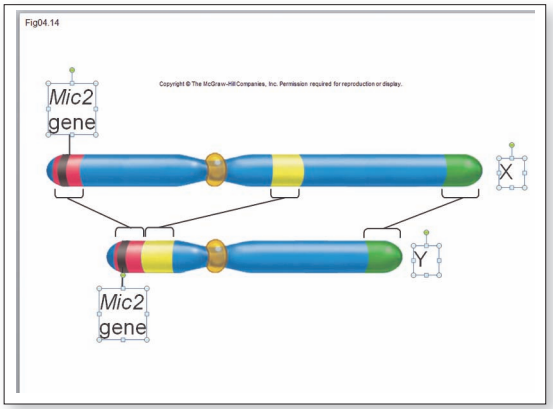
Presentation Tools

Within Connect, you will find presentation materials to enhance your class all in one place.

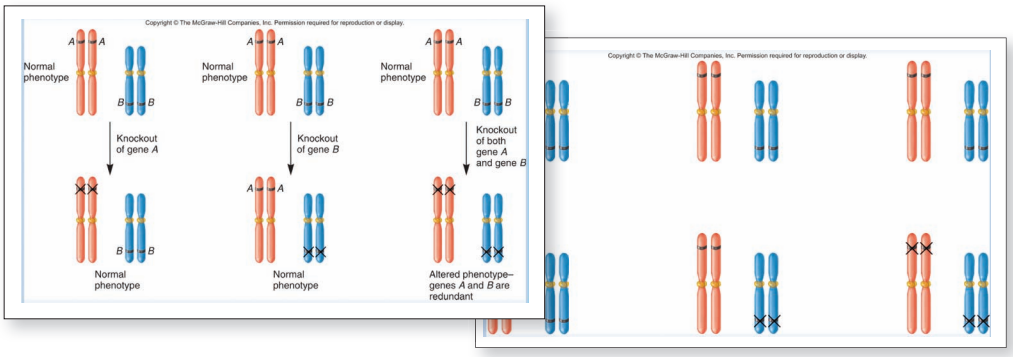


Animation PowerPoints contain full-color animations illustrating important processes, which are fully embedded in PowerPoint slides for easy use in your presentations.

Lecture PowerPoints with animations fully embedded.



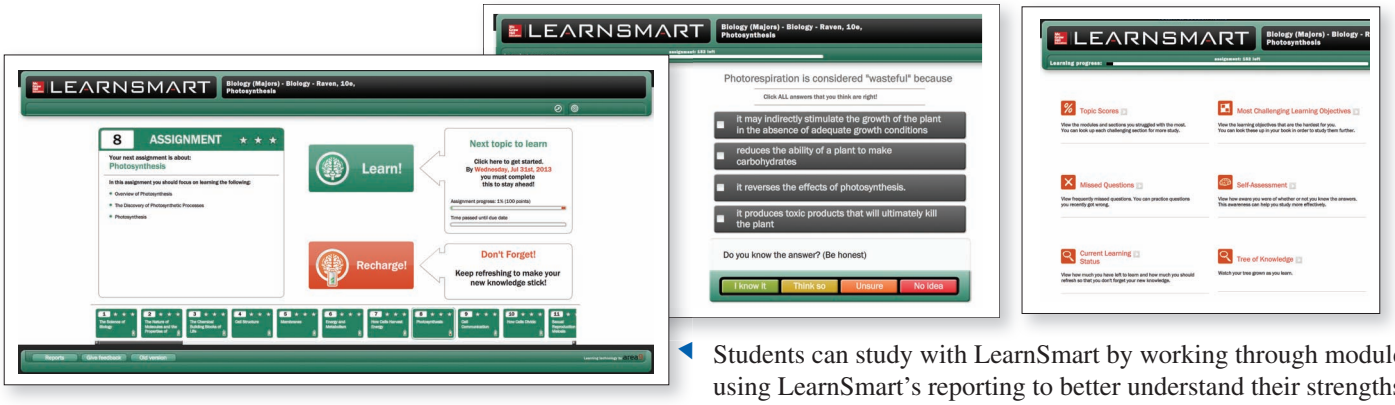
FlexArt PowerPoints contain editable art from the text. For all figures, labels and leader lines are editable, and some figures also have editable or stepped-out art, allowing you to customize your PowerPoint presentations.



Labeled and unlabeled JPEG files of all art and photos in the text to be readily incorporated into presentations, exams, or custom-made classroom materials.

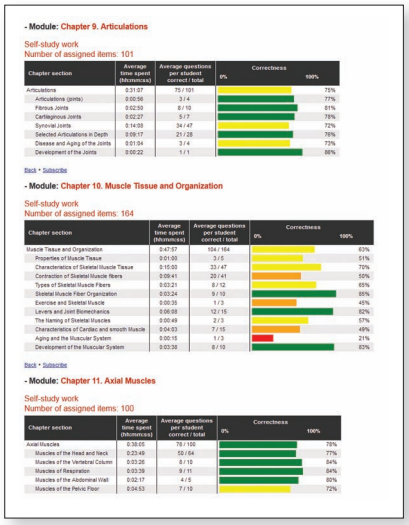
LEARNSMART ADVANTAGE

LearnSmart Advantage® is a new series of adaptive learning products including SmartBook fueled by LearnSmart—the most widely used adaptive learning resource proven to strengthen memory recall, increase retention, and boost grades.



Students can study with LearnSmart by working through modules and using LearnSmart's reporting to better understand their strengths and weaknesses.

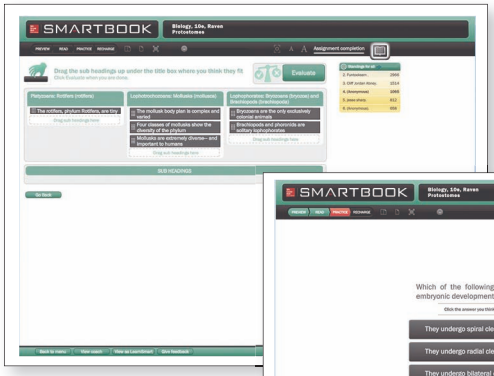
Students can Download the LearnSmart app from iTunes or Google Play and work on LearnSmart from anywhere!



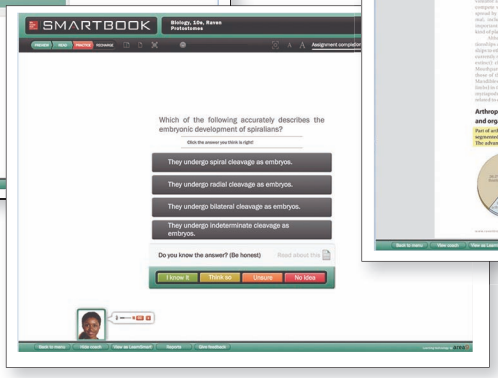
Reports in Connect and LearnSmart help you monitor student assignments and performance, allowing for "just-in-time" teaching to clarify concepts that are more difficult for your students to understand.

SMARTBOOK®

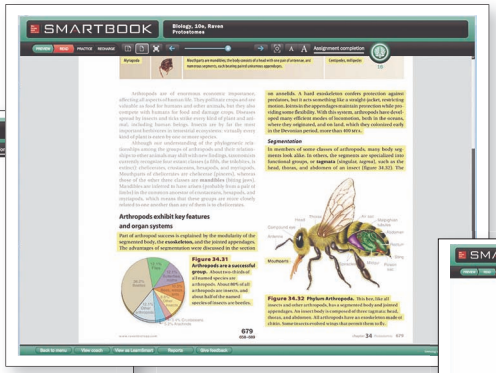
Powered by an intelligent diagnostic and adaptive engine, **SmartBook®** facilitates the reading process by identifying what content a student knows and doesn't know through adaptive assessments.



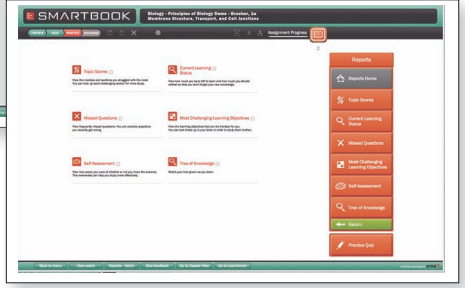
The Smartbook experience starts by previewing key concepts from the chapter and ensuring that you understand the big ideas.



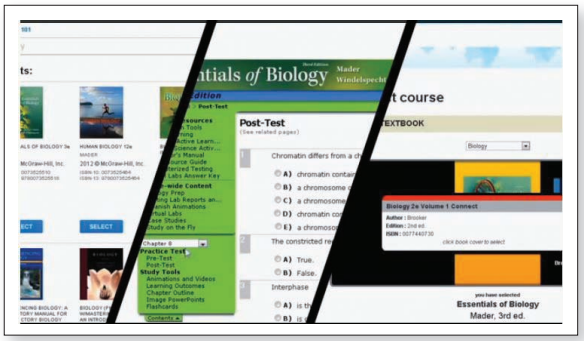
SmartBook asks you questions that identify gaps in your knowledge. The reading experience then continuously adapts in response to the assessments, highlighting the material you need to review based on what you don't know.

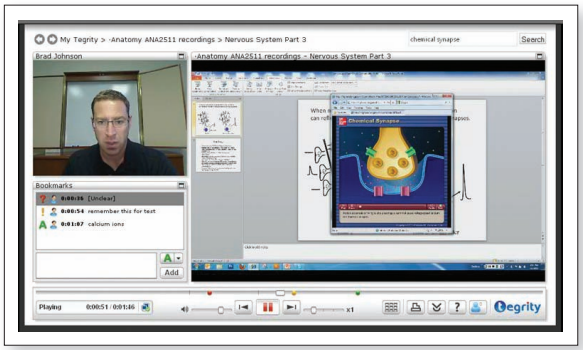


The reports in SmartBook help identify topics where you need more work.



Campus MH Campus® integrates all of your digital products from McGraw-Hill Education with your school LMS for quick and easy access to best-in-class content and learning tools.





Tegrity Campus is a fully automated lecture capture solution used in traditional, hybrid, "flipped classes" and online courses to record lessons, lectures, and skills. Its personalized learning features make study time incredibly efficient, and its ability to affordably scale brings this benefit to every student on campus. Patented search technology and real-time LMS integrations make Tegrity the market-leading solution and service. More than just a recorded lecture, Tegrity lets you search and bookmark content, take notes, and work with fellow classmates in order to make learning incredibly efficient.

ACKNOWLEDGMENTS

The production of a textbook is truly a collaborative effort, and I am greatly indebted to a variety of people. This textbook has gone through multiple rounds of rigorous revision that involved the input of faculty, students, editors, and educational and media specialists. Their collective contributions are reflected in the final outcome.

Let me begin by acknowledging the many people at McGraw-Hill Education whose efforts are amazing. My highest praise goes to Rebecca Olson (Executive Brand Manager) who managed many aspects of this project. I also would like to thank Elizabeth Sievers (Director of Development–Biology), for her patience in overseeing this project and her contributions to the digital components. Other people at McGraw-Hill have played key roles in producing an actual book and the supplements that go along with it. In particular, Jayne Klein (Content Project Manager) has done a superb job of managing the components that need to be assembled to produce a book. I would also like to thank John Leland (Content Licensing Specialist), who acted as an interface between me and the photo company. In addition, my gratitude goes to David Hash (Designer), who provided much input into the internal design of the book as well as creating an awesome cover. Finally, I would like to thank Patrick Reidy (Marketing Manager), whose major efforts begin once the book is published!

With regard to the content of the book, Deborah Brooker (Freelance Developmental Editor) has worked closely with me in developing the art for this textbook. She has scrutinized each figure for clarity and logic. I would also like to thank Kevin Campbell (Freelance Copy Editor) for making grammatical improvements throughout the text and art, which has significantly improved the text's clarity.

I would also like to extend my thanks to everyone at SPI Global, including the many artists who have played important roles in developing the art for this textbook. Also, the folks at SPI Global worked with great care in the paging of the book, making sure that the figures and relevant text are as close to each other as possible. Likewise, the people at Photo Affairs, inc. have done a great job of locating many of the photographs that have been used in this textbook.

Finally, I want to thank the many scientists who reviewed the chapters of this textbook. Their broad insights and constructive suggestions were an important factor that shaped its final content and organization. I am truly grateful for their time and effort.

REVIEWERS

First Edition

Preston Aldrich, *Benedictine University*
Diya Banerjee, *Virginia Tech University*
Vernon W. Bauer, *Francis Marion University*
Mark Brick, *Colorado State University*
Aaron Cassill, *University of Texas at San Antonio*
Bruce Chase, *University of Nebraska at Omaha*
Erin Cram, *Northeastern University*
Sandra L. Davis, *University of Indianapolis*
Steve Denison, *Eckerd College*
Michele Engel, *University of Colorado–Denver*
Jayant Ghiara, *University of California–San Diego*
Meredith Hamilton, *Oklahoma State University*
Stephen C. Hedman, *University of Minnesota*
Robert Hinrichsen, *Indiana University of Pennsylvania*
David Kass, *Eastern Michigan University*
Ekaterina N. Kaverina, *East Tennessee State University*
Sarah Kenick, *University of New Hampshire*
Michael Kielb, *Eastern Michigan University*
Brian Kreiser, *University of Southern Mississippi*
Michael Lehmann, *University of Arkansas*
Haiying Liang, *Clemson University*
Shawn Meagher, *Western Illinois University*
Marcie Moehnke, *Baylor University*
Roderick M. Morgan, *Grand Valley State University*
James Morris, *Clemson University*
Sang-Chul Nam, *Baylor University, Waco, TX*
John C. Osterman, *University of Nebraska–Lincoln*
William A. Rosche, *Richard Stockton College of New Jersey*
Lara Soowal, *University of California–San Diego*
Tzvi Tzfira, *University of Michigan*
Timothy Walston, *Truman State University*
Yunqiu Wang, *University of Miami*
Cindy White, *University of Northern Colorado*
Malcolm Zellars, *Georgia State University*
Jianzhi Zhang, *University of Michigan*

Second Edition

Agnes Ayme-Southgate, *College of Charleston*
Jose Barbosa, *University of Tennessee–Chattanooga*
Dena Berg, *Tarrant County College NW*
David Carlini, *American University*
Aaron Cassill, *University of Texas–San Antonio*
Norman Clippinger, *Metropolitan State Univerity of Denver*
Marian Gardner, *North Carolina State University*
Elliott S. Goldstein, *Arizona State University*
Elena Keeling, *California Polytechnic State University*
Hsiu-Ping Liu, *Metropolitan State University of Denver*
Helen Piontkivska, *Kent State University*
Rongsun Pu, *Kean University*
Estella Chen Quin, *Kennesaw State University*
Larissa Walker, *University of Mobile*
Timothy Walston, *Truman State University*
Robert Wisotzkey, *California State University–East Bay*

A Visual Guide to
CONCEPTS OF GENETICS

LEARNING THROUGH EXPERIMENTATION

Many chapters contain an experiment that is presented according to the scientific method. These experiments are integrated within the chapters and flow with the rest of the textbook. As you read the experiments, which can be hypothesis-testing or discovery-based science, you will simultaneously explore the scientific method and the genetic principles learned from this approach.

BACKGROUND OBSERVATIONS

Each experiment begins with a description of the information that led researchers to study a hypothesis-driven or discovery-based problem. Detailed information about the researchers and the experimental challenges they faced help students to understand actual research.

Morgan's Experiments Showed a Connection Between a Genetic Trait and the Inheritance of a Sex Chromosome in *Drosophila*

In the early 1900s, Thomas Hunt Morgan carried out the first study that confirmed the location of a gene on a particular chromosome. In this experiment, he showed that a gene affecting eye color in fruit flies is located on the X chromosome. Morgan was trained as an embryologist, and much of his early research involved descriptive and experimental work in that field. He was particularly interested in ways that organisms change. He wrote, "The most distinctive problem of zoological work is the change in form that animals undergo, both in the course of their development from the egg (

THE HYPOTHESIS OR THE GOAL

The student is given a possible explanation for the observed phenomenon that will be tested or the question researchers were hoping to answer. This section reinforces the scientific method and allows students to experience the process for themselves.

▶ THE GOAL (DISCOVERY-BASED SCIENCE)

This is an example of discovery-based science rather than hypothesis testing. In this case, a quantitative analysis of genetic crosses may reveal the inheritance pattern for the white-eye allele.

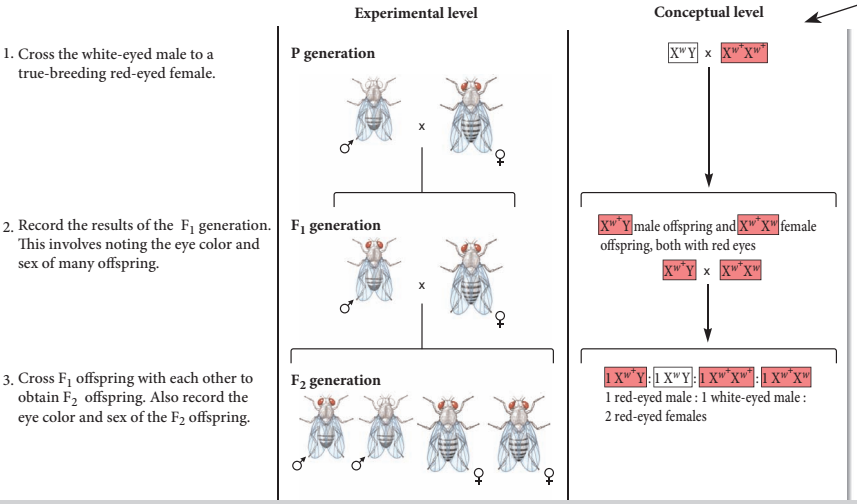
TESTING THE HYPOTHESIS OR ACHIEVING THE GOAL

This section illustrates the experimental process, including the actual steps followed by scientists to test their hypothesis or study a question. Science comes alive for students with this detailed look at experimentation.

▶ **ACHIEVING THE GOAL — FIGURE 4.9 Inheritance pattern of an X-linked trait in fruit flies.**

Starting material: A true-breeding line of red-eyed fruit flies plus one white-eyed male fly that was discovered in Morgan's collection of flies.

Concept Check: What is the key result that suggests an X-linked inheritance pattern?



THE DATA

Actual data from the original research paper help students understand how real-life research results are reported. Each experiment's results are discussed in the context of the larger genetic principle to help students understand the implications and importance of the research.

▶ **THE DATA**

Cross	*Results*	
Original white-eyed male to a red-eyed female	F_1 generation:	All red-eyed flies
F_1 male to F_1 females	F_2 generation:	2,459 red-eyed females 1,011 red-eyed males 0 white females 782 white-eyed males
White-eyed males to F_1 females	Testcross:	129 red-eyed females 132 red-eyed males 88 white-eyed females 86 white-eyed males

Data from T. H. Morgan (1910) Se

INTERPRETING THE DATA

This discussion, which examines whether the experimental data supported or disproved the hypothesis or provided new information to propose a hypothesis, gives students an appreciation for scientific interpretation.

▶ **INTERPRETING THE DATA**

As seen in The Data, the F_2 generation consisted of 2459 red-eyed females, 1011 red-eyed males, and 782 white-eyed males. Most notably, no white-eyed female offspring were observed in the F_2 generation. These results suggested that the pattern of transmission from parent to offspring depends on the sex of the offspring and on the alleles that they carry. As shown in the Punnett square here, the data are consistent with the idea that the eye color alleles are located on the X chromosome:

F_1 male is $X^{w+}Y$
F_1 female is $X^{w+}X^w$

Female gametes \ Male gametes	♂ X^{w+}	Y
♀ X^{w+}	$X^{w+}X^{w+}$ Red, female	$X^{w+}Y$ Red, male
X^w	$X^{w+}X^w$ Red, female	X^wY White, male

The Punnett square predicts that the F_2 generation will not have any white-eyed females. This prediction was confirmed experimentally. These results indicated that the eye color alleles are located on the X chromosome. As mentioned earlier, genes that are physically located within the X chromosome are called X-linked genes, or **X-linked alleles.** However, it should also be pointed out that

Learning–Assessment–Problem Solving

These study tools and problems are crafted to aid students in reviewing key information in the text, assess their understanding, and develop problem-solving skills.

4.3 PROPERTIES OF THE X AND Y CHROMOSOMES IN MAMMALS

Learning Outcomes:

1. Compare and contrast the features of the X and Y chromosomes in mammals.
2. Explain how pseudoautosomal inheritance occurs.

As discussed at the beginning of this chapter, sex determination in mammals is determined by the presence of the Y chromosome, which carries the *Sry* gene. The X and Y chromosomes also differ in other ways. The X chromosome is typically much larger than

NEW! LEARNING OUTCOMES

Each section begins with one or more Learning Outcomes. These allow a student to appreciate the skills and knowledge they will gain if they master the material.

REVIEWING THE KEY CONCEPTS

These bulleted lists at the end of each section help students identify important concepts. Students should understand these concepts before moving on to the next section.

4.2 REVIEWING THE KEY CONCEPTS

- Dosage compensation often occurs in species that differ in their sex chromosomes (see Table 4.1).
- In mammals, the process of X-chromosome inactivation (XCI) in females compensates for the single X chromosome found in males. The inactivated X chromosome is called a Barr body. The process can lead to a variegated phenotype, such as a calico cat (see Figure 4.5).
- After it occurs during embryonic development, the pattern of X-chromosome inactivation is maintained when cells divide (see Figure 4.6).
- X-chromosome inactivation is controlled by the X-inactivation center (Xic) that contains the *Xist* gene. XCI occurs as initiation, spreading, and maintenance phases (see Figure 4.7).

COMPREHENSION QUESTIONS

Multiple choice questions found at the end of each section allow students an opportunity to test their knowledge of key information and concepts. This helps students better identify what they know and don't know before tackling more concepts. Answers are provided at the end of the chapter.

4.2 COMPREHENSION QUESTIONS

1. In fruit flies, dosage compensation is achieved by
   a. X-chromosome inactivation.
   b. turning up the expression of genes on the single X chromosome in the male twofold.
   c. turning down the expression of genes on the two X chromosomes in the female to one-half.
   d. all of the above.
2. According to the Lyon hypothesis,
   a. one of the X chromosomes is converted to a Barr body in somatic cells of female mammals.
   b. one of the X chromosomes is converted to a Barr body in all cells of female mammals.
   c. both of the X chromosomes are converted to Barr bodies in somatic cells of female mammals.
   d. both of the X chromosomes are converted to Barr bodies in all cells of female mammals.
3. Which of the following is *not* a phase of XCI?
   a. Initiation
   b. Spreading
   c. Maintenance
   d. Erasure

GENES → TRAITS

Because genetics is such a broad discipline ranging from the molecular level to populations, many students have trouble connecting the concepts they learn in molecular genetics with the traits that occur at the level of an organism. To make this connection more meaningful, certain figures have a "Genes→Traits" feature that reminds students that molecular and cellular phenomena ultimately lead to traits observed in organisms.

CONCEPT CHECK QUESTIONS

Students can test their knowledge and understanding with Concept Check questions that are associated with the figure legends. These questions often go beyond simple recall of information and ask students to apply or interpret information presented in the illustrations.

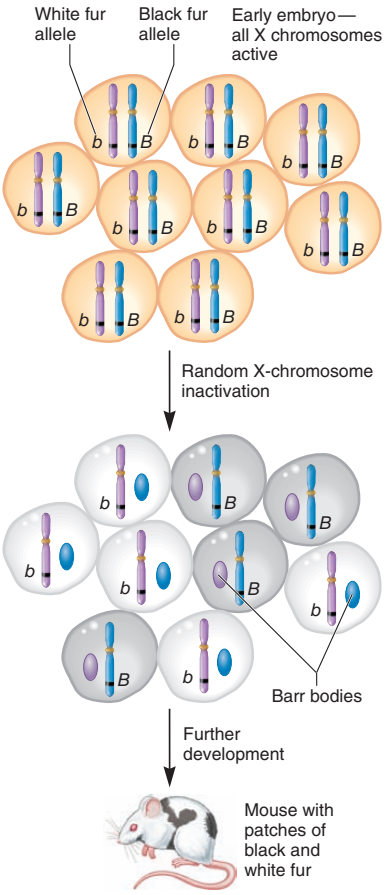


FIGURE 4.6 The mechanism of X-chromosome inactivation.

Genes → Traits The top of this figure represents a mass of several cells that compose the early embryo. Initially, both X chromosomes are active. At an early stage of embryonic development, random inactivation of one X chromosome occurs in each cel This inactivation pattern is maintained as the embryo matures into an adult.

Concept Check: At which stage of development does X-chromosome inactivation initially occur?

Genetic TIPS

The Question: A cat is born with two X chromosomes and one Y chromosome. One of the X chromosomes carries the black allele and the other carries the orange allele. Would you expect this cat to be a male or female? Would it be calico?

Topic: What topic(s) in genetics does this question address?

The topics are sex determination and X-chromosome inactivation.

Information: What information do you know based on the question and based on your understanding of the topic?

From the question, you know the composition of sex chromosomes in a cat and which alleles are found on the X chromosomes. From your understanding of the topics, you may remember that the Y chromosome determines maleness in mammals, and that X-chromosome inactivation occurs such that one X chromosome remains active in somatic cells.

Problem-Solving Strategy: Predict the outcome.

With regard to sex determination, you would predict that the cat is a male because the Y chromosome causes maleness. You would also predict that random X-chromosome inactivation would occur in this cat's somatic cells, because the cells contain two X chromosomes.

Answer: It would be a male cat with a calico coat.

NEW! GENETIC TIPS

*Problem solving is a skill genetics students need to master. **Genetic TIPS** provides a consistent approach to help students solve problems in genetics. This approach has three components. First, the student is made aware of the **T**opic at hand. Second, the question is evaluated with regard to the **I**nformation that is available to the student. Finally, the student is guided through a **P**roblem-Solving **S**trategy to tackle the question. Additional **Genetic TIPS** are presented at the end of the chapter, allowing for more practice in strengthening problem-solving skills.*

End-of-Chapter Support Materials

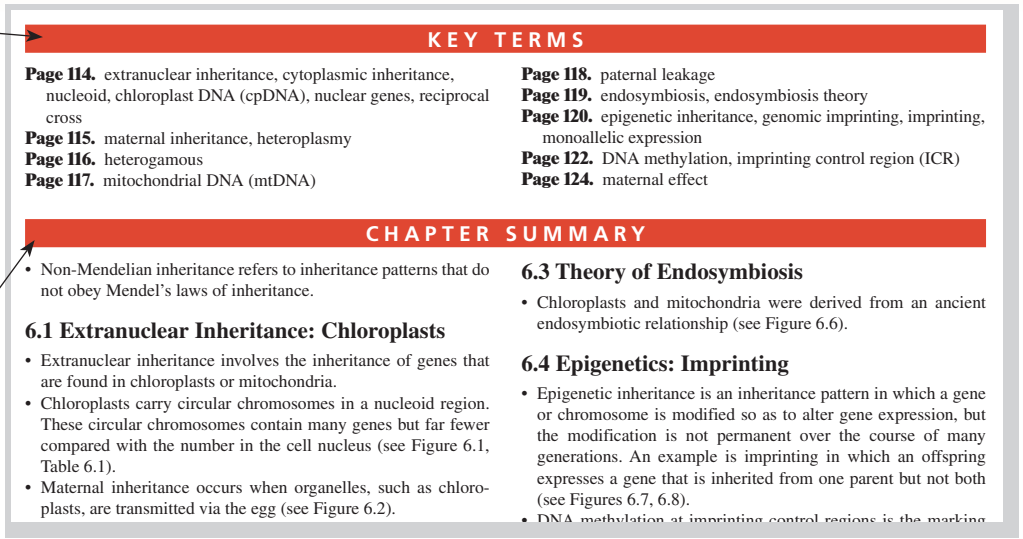
These study tools and problems are crafted to aid students in reviewing key information in the text and developing a wide range of problem-solving skills. They also develop a student's cognitive, writing, analytical, computational, and collaborative abilities.

KEY TERMS

Providing the key terms from the chapter enhances student development of vital vocabulary necessary for the understanding and application of chapter content. Important terms are boldfaced throughout the chapter and page referenced at the end of each chapter for reflective study.

CHAPTER SUMMARY

These bulleted summaries organized by section emphasize the main concepts of the chapter to provide students with a thorough review of the main topics covered.



KEY TERMS

Page 114. extranuclear inheritance, cytoplasmic inheritance, nucleoid, chloroplast DNA (cpDNA), nuclear genes, reciprocal cross
Page 115. maternal inheritance, heteroplasmy
Page 116. heterogamous
Page 117. mitochondrial DNA (mtDNA)
Page 118. paternal leakage
Page 119. endosymbiosis, endosymbiosis theory
Page 120. epigenetic inheritance, genomic imprinting, imprinting, monoallelic expression
Page 122. DNA methylation, imprinting control region (ICR)
Page 124. maternal effect

CHAPTER SUMMARY

- Non-Mendelian inheritance refers to inheritance patterns that do not obey Mendel's laws of inheritance.

6.1 Extranuclear Inheritance: Chloroplasts

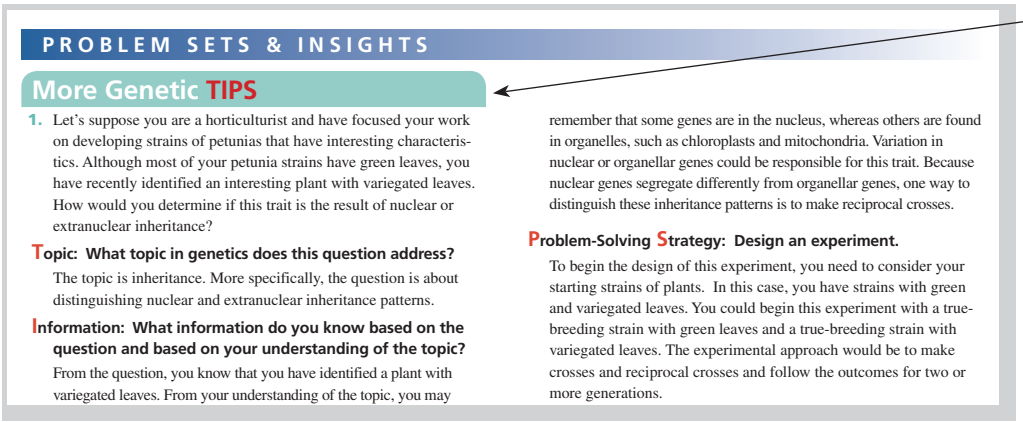
- Extranuclear inheritance involves the inheritance of genes that are found in chloroplasts or mitochondria.
- Chloroplasts carry circular chromosomes in a nucleoid region. These circular chromosomes contain many genes but far fewer compared with the number in the cell nucleus (see Figure 6.1, Table 6.1).
- Maternal inheritance occurs when organelles, such as chloroplasts, are transmitted via the egg (see Figure 6.2).

6.3 Theory of Endosymbiosis

- Chloroplasts and mitochondria were derived from an ancient endosymbiotic relationship (see Figure 6.6).

6.4 Epigenetics: Imprinting

- Epigenetic inheritance is an inheritance pattern in which a gene or chromosome is modified so as to alter gene expression, but the modification is not permanent over the course of many generations. An example is imprinting in which an offspring expresses a gene that is inherited from one parent but not both (see Figures 6.7, 6.8).
- DNA methylation at imprinting control regions is the marking



PROBLEM SETS & INSIGHTS

More Genetic TIPS

1. Let's suppose you are a horticulturist and have focused your work on developing strains of petunias that have interesting characteristics. Although most of your petunia strains have green leaves, you have recently identified an interesting plant with variegated leaves. How would you determine if this trait is the result of nuclear or extranuclear inheritance?

Topic: What topic in genetics does this question address?

The topic is inheritance. More specifically, the question is about distinguishing nuclear and extranuclear inheritance patterns.

Information: What information do you know based on the question and based on your understanding of the topic?

From the question, you know that you have identified a plant with variegated leaves. From your understanding of the topic, you may remember that some genes are in the nucleus, whereas others are found in organelles, such as chloroplasts and mitochondria. Variation in nuclear or organellar genes could be responsible for this trait. Because nuclear genes segregate differently from organellar genes, one way to distinguish these inheritance patterns is to make reciprocal crosses.

Problem-Solving Strategy: Design an experiment.

To begin the design of this experiment, you need to consider your starting strains of plants. In this case, you have strains with green and variegated leaves. You could begin this experiment with a true-breeding strain with green leaves and a true-breeding strain with variegated leaves. The experimental approach would be to make crosses and reciprocal crosses and follow the outcomes for two or more generations.

NEW! MORE GENETIC TIPS

*Like the Genetic TIPS within the chapter, these problems provide more practice in developing problem-solving skills before the students work through more problems unaided. The Genetic TIPS help the student identify the primary question (the **T**opic), evaluate the question based on the student's knowledge of the topic (**I**nformation), and then the student is guided through the solution revealing a **P**roblem-Solving **S**trategy. These provide a reference for when students encounter similar problems later.*

CONCEPTUAL QUESTIONS

These questions test the understanding of basic genetic principles. The student is given many questions with a wide range of difficulty. Some require critical thinking skills, and some require the student to write coherent answers in an essay form.

Conceptual Questions

C1. What is extranuclear inheritance? Describe three examples.

C2. Among different species, does extranuclear inheritance always low a maternal inheritance pattern? Why or why not?

C3. Extranuclear inheritance often correlates with maternal inherit Even so, paternal leakage can occur. What is paternal leakage? If a cross produced 200 offspring and the level of mitochondri paternal leakage was 3%, how many offspring would be expec to contain paternal mitochondria?

C4. Discuss the structure and organization of the mitochondrial an chloroplast genomes. How large are they, how many genes do contain, and how many copies of the genome are found in each organelle?

C5. Explain the likely evolutionary origin of chloroplast and mitoc drial genomes. How have the sizes of the chloroplast and mito- chondrial genomes changed since their origin? How did this oc

C6. Which of the following traits or diseases are determined by nu genes?

A. Snail-coiling pattern

B. Dwarfism in mice due to a mutation in *Igf2*

C. Variegated leaf color in the four-o'clock plant

APPLICATION AND EXPERIMENTAL QUESTIONS

These questions test the ability to analyze data, design experiments, or appreciate the relevance of experimental techniques.

Application and Experimental Questions

E1. A variegated trait in plants is analyzed using reciprocal crosses. The following results are obtained:

Variegated female × Normal male → 1024 variegated + 52 normal

Normal female × Variegated male → 1113 normal + 61 variegated

Explain this pattern of inheritance.

E2. Two male mice, which we will call male A and male B, are both phenotypically normal. Male A was from a litter that contained half phenotypically normal mice and half dwarf mice. The mother of male A was known to be homozygous for the normal *Igf2* allele. Male B was from a litter of eight mice that were all phenotypically normal. The parents of male B were a phenotypically normal male and a dwarf female. Male A and male B were put into a cage with two female mice that we will call female A and female B. Female A is dwarf, and female B is phenotypically normal. The parents of these two females were unknown, although it was known that they were from the same litter. The mice were allowed to mate with each other, and the following data were obtained:

Female A gave birth to three dwarf babies and four normal babies.

Female B gave birth to four normal babies and two dwarf babies.

Which male(s) mated with female A and female B? Explain.

E3. Figure 6.10 describes an example of a maternal effect gene. Explain how Sturtevant deduced a maternal effect gene based on the F_2 and F_3 generations.

E4. Chapter 20 describes three blotting methods (i.e., Southern blotting, Northern blotting, and Western blotting) that are used to detect specific genes and gene products. Southern blotting detects

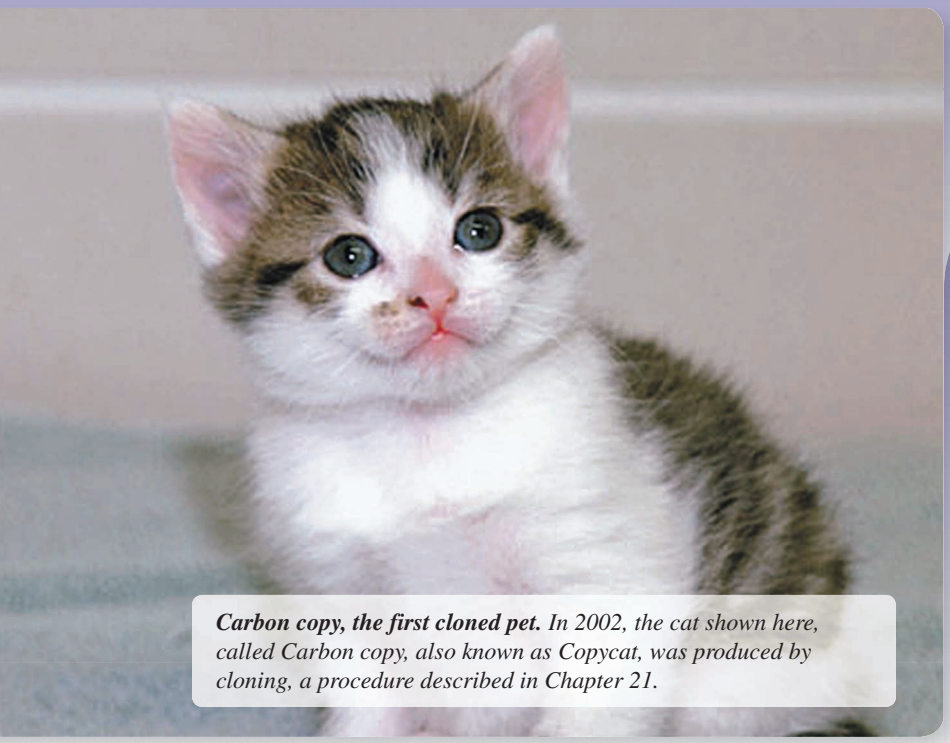
QUESTIONS FOR STUDENT DISCUSSION/ COLLABORATION

These questions encourage students to consider broad concepts and practical problems. Some questions require a substantial amount of computational activities, which can be worked on as a group.

Questions for Student Discussion/Collaboration

1. During the course of evolution, most organellar genes have been transferred from the chloroplast or mitochondrial genome to the nuclear genome. Discuss possible reasons why this may have occurred. In other words, what are possible selective advantages to having genes in the nucleus?
2. Recessive maternal effect genes are identified in flies (for example) when a phenotypically normal mother cannot produce any normal offspring. Because all of the offspring are dead, this female fly cannot be used to produce a strain of heterozygous flies that could be used in future studies. How would you identify heterozygous individuals that are carrying a recessive maternal effect allele? How would you maintain this strain of flies in a laboratory over many generations?

1



Carbon copy, the first cloned pet. *In 2002, the cat shown here, called Carbon copy, also known as Copycat, was produced by cloning, a procedure described in Chapter 21.*

CHAPTER OUTLINE

OVERVIEW OF GENETICS

Hardly a week goes by without a major news story involving a genetic breakthrough. The increasing pace of genetic discoveries has become staggering. The Human Genome Project is a case in point. This project began in the United States in 1990, when the National Institutes of Health and the Department of Energy joined forces with international partners to decipher the massive amount of information contained in our **genome**—the **deoxyribonucleic acid (DNA)** found within all of our chromosomes (**Figure 1.1**). Working collectively, a large group of scientists from around the world produced a detailed series of maps that help geneticists navigate through human DNA. Remarkably, in only a decade, they determined the DNA sequence of 90% of the human genome. The first draft of this sequence, published in 2001, was nearly 3 billion nucleotide base pairs in length. The completed sequence, published in 2003, has an accuracy greater than 99.99%; fewer than one mistake was made in every 10,000 base pairs (bp)!

Studying the human genome allows us to explore fundamental details about ourselves at the molecular level. The results of the Human Genome Project have shed considerable light on basic questions, such as how many genes we have, how genes direct the activities of living cells, how species evolve, how single cells develop into complex tissues, and how defective genes cause disease. Furthermore, such understanding may lend itself to improvements in modern medicine by providing better diagnoses of diseases and the development of new treatments for them.

The journey to unravel the mysteries within our genes has involved the invention of many new technologies. This textbook emphasizes a large number of these modern approaches. For example, new technologies have made it possible to produce medicines that would otherwise be difficult or impossible to make. An example is human recombinant insulin, which is synthesized in strains of *Escherichia coli* bacteria that have been genetically altered by the addition of genes that encode the functional regions of human insulin. The bacteria are grown in a laboratory and make large amounts of human insulin, which is purified and administered to millions of people with insulin-dependent diabetes. Chapter 21 describes the production of insulin in greater detail and also examines other ways that genetic approaches have applications in the area of biotechnology.

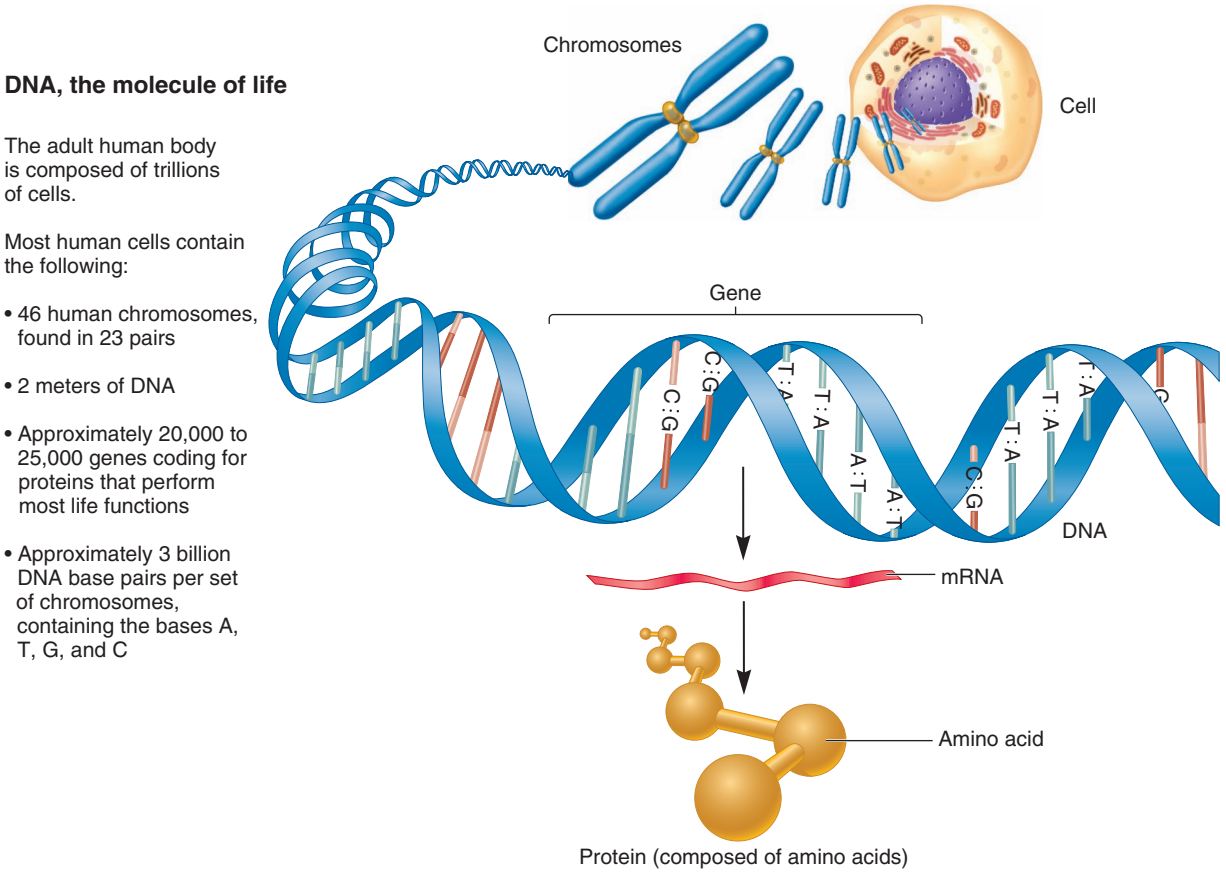


FIGURE 1.1 **The Human Genome Project.** The human genome is a complete set of human chromosomes. People have two sets of chromosomes, one from each parent. Collectively, each set of chromosomes is composed of a DNA sequence that is approximately 3 billion nucleotide base pairs long. Estimates suggest that each set contains about 22,000 genes. This figure emphasizes the DNA found in the cell nucleus. Humans also have a small amount of DNA in their mitochondria, which has also been sequenced.

Concept Check: *How might a better understanding of our genes be used in the field of medicine?*

A controversial example of a genetic technology is mammalian cloning. In 1997, Ian Wilmut and his colleagues produced clones of sheep, using mammary cells from an adult animal (**Figure 1.2**). More recently, such cloning has been achieved in several mammalian species, including cows, mice, goats, pigs, and cats. In 2002, the first pet was cloned, a cat named Carbon copy, also known as Copycat (see photo at the beginning of the chapter). The cloning of mammals provides the potential for many practical applications. Cloning of livestock would enable farmers to use cells from their best individuals to create genetically homogeneous herds. This could be advantageous in terms of agricultural yield, although such a genetically homogeneous herd may be more susceptible to certain diseases. However, people have become greatly concerned with the possibility of human cloning. As discussed in Chapter 21, this prospect has raised serious ethical questions. Within the past few years, legislative bills have been introduced that involve bans on human cloning.

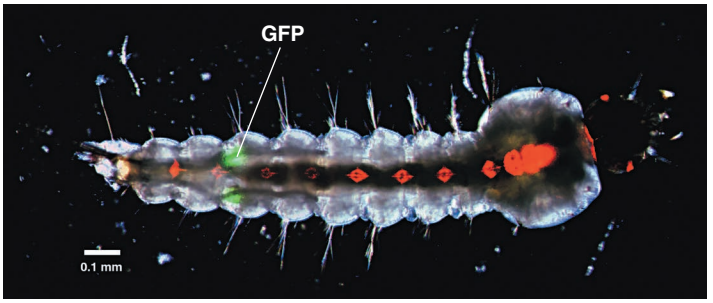
Finally, genetic technologies provide the means of modifying the traits of animals and plants in ways that would have been unimaginable just a few decades ago. **Figure 1.3a** illustrates a bizarre example in which scientists introduced a gene from jellyfish into mice. Certain species of jellyfish emit a "green glow" produced by a gene that encodes a bioluminescent protein called green fluorescent protein (GFP). When exposed to blue or ultraviolet (UV) light, the protein emits a striking green-colored light. Scientists were able to clone the *GFP* gene from a sample of jellyfish cells and then introduce this gene into laboratory mice. The green fluorescent protein is made throughout the cells of their bodies. As a result, their skin, eyes, and organs give off an eerie green glow when exposed to UV light.

The expression of green fluorescent protein allows researchers to identify particular proteins in cells or specific body parts. For example, Andrea Crisanti and colleagues have altered mosquitoes to express GFP only in the gonads of males (**Figure 1.3b**). This enables the researchers to identify and sort males from females.

FIGURE 1.2 The cloning of a mammal. The lamb on the left is Dolly, the first mammal to be cloned. She was cloned from a cell of a Finn Dorset (a white-faced sheep). The sheep on the right is Dolly's surrogate mother, a Blackface ewe. A description of how Dolly was produced is presented in Chapter 21.

Concept Check: What ethical issues may be associated with human cloning?

(a) GFP expressed in mice



(b) GFP expressed in the gonads of a male mosquito

FIGURE 1.3 The introduction of a jellyfish gene into laboratory mice and mosquitoes. **(a)** A gene that naturally occurs in the jellyfish encodes a protein called green fluorescent protein (GFP). The *GFP* gene was cloned and introduced into mice. When these mice are exposed to ultraviolet light, GFP emits a bright green color. These mice glow green, just like jellyfish! **(b)** GFP was introduced next to a gene sequence that causes the expression of GFP only in the gonads of male mosquitoes. This allows researchers to identify and sort males from females.

Concept Check: Why is it useful to sort male mosquitoes from female mosquitoes?

Why is this useful? The ability to rapidly sort mosquitoes by sex makes it possible to produce populations of sterile males and then release the sterile males without the risk of releasing additional females. The release of sterile males may be an effective means of controlling mosquito populations because females breed only once. Mating with a sterile male prevents a female from producing offspring. In 2008, Osamu Shimomura, Martin Chalfie, and Roger Tsien received the Nobel Prize in chemistry for the discovery and the development of GFP, which has become a widely used tool in biology.

Overall, as we move forward in the twenty-first century, the excitement level in the field of genetics is high, perhaps higher than it has ever been. Nevertheless, the excitement generated by new genetic knowledge and technologies will also create many ethical and societal challenges. In this chapter, we begin with an overview of genetics and then explore the various fields of genetics and their experimental approaches.

1.1 THE MOLECULAR EXPRESSION OF GENES

Learning Outcomes:

1. Describe the biochemical composition of cells.
2. Outline how DNA stores the information to make proteins.
3. Explain how proteins are largely responsible for cell structure and function.

Genetics is the branch of biology that deals with heredity and variation. It stands as the unifying discipline in biology by allowing us to understand how life can exist at all levels of complexity, ranging from the molecular to the population level. Genetic variation is the root of the natural diversity that we observe among members of the same species as well as among different species.

Genetics is centered on the study of genes. A gene is classically defined as a unit of heredity, but such a vague definition does

not do justice to the exciting characteristics of genes as intricate molecular units that manifest themselves as critical contributors to cell structure and function.

- At the molecular level, a **gene** is a segment of DNA that has the information to produce a functional product. The functional product of most genes is a polypeptide—a linear sequence of amino acids that folds into units that constitute proteins.
- Genes are commonly described according to the way they affect **traits,** which are the characteristics of an organism. In humans, for example, we speak of traits such as eye color, hair texture, and height. An ongoing theme of this textbook is the relationship between genes and traits. As an organism grows and develops, its collection of genes provides a blueprint that determines its characteristics.

In this section, we will examine the general features of life with an emphasis on the molecular level. Genetics is the common thread that explains the existence of life and its continuity from generation to generation. For most students, this chapter should serve as a cohesive review of topics they learned in other introductory courses such as general biology. Even so, it is usually helpful to see the "big picture" of genetics before delving into the finer details that are covered in Chapters 2 through 26.

Living Cells Are Composed of Biochemicals

To fully understand the relationship between genes and traits, we need to begin with an examination of the composition of living organisms. Every cell is constructed from intricately organized chemical substances. Small organic molecules such as glucose and amino acids are produced from the linkage of atoms via chemical bonds. The chemical properties of organic molecules are essential for cell vitality in two key ways.

- First, the breaking of chemical bonds during the degradation of small molecules provides energy to drive cellular processes.
- A second important function of these small organic molecules is their role as the building blocks for the synthesis of larger molecules. Four important categories of larger cellular molecules are **nucleic acids** (i.e., DNA and RNA), **proteins, carbohydrates,** and **lipids.** Three of these—nucleic acids, proteins, and carbohydrates—form **macromolecules** that are composed of many repeating units of smaller building blocks. Proteins, RNA, and carbohydrates can be made from hundreds or even thousands of repeating building blocks. DNA is the largest macromolecule found in living cells. A single DNA molecule can be composed of a linear sequence of hundreds of millions of nucleotides!

The formation of cellular structures relies on the interactions of molecules and macromolecules. **Figure 1.4** illustrates this concept.

- Nucleotides are small organic molecules.
- Nucleotides are linked to each other and form the building blocks of DNA, which is a macromolecule.
- DNA is a component of chromosomes, which also contain proteins that contribute to chromosome structure.
- Within a eukaryotic cell, the chromosomes are contained in a compartment called the cell nucleus. The nucleus is bounded by a double membrane composed of lipids and proteins that shields the chromosomes from the rest of the cell. The nucleus is an example of an **organelle**—a membrane-bound compartment with a specialized function. The cell nucleus protects the chromosomes from mechanical damage and provides a single compartment for genetic activities such as gene transcription.
- Finally, cellular molecules, macromolecules, and organelles are organized to make a complete living cell.

Each Cell Contains Many Different Proteins That Determine Cell Structure and Function

To a great extent, the characteristics of a cell depend on the types of proteins that it makes. All of the proteins that a cell or organism makes at a given time is called its **proteome.** As we will learn throughout this textbook, proteins are the "workhorses" of all living cells. The range of functions among different types of proteins is truly remarkable. Some examples include the following:

- Proteins help determine the shape and structure of a given cell. For example, the protein known as tubulin can assemble into large structures known as microtubules, which provide the cell with internal structure and organization.
- Proteins are inserted into cell membranes and aid in the transport of ions and small molecules across the membrane.
- Proteins may also function as biological motors. An interesting case is the protein known as myosin, which is involved in the contractile properties of muscle cells.
- Within multicellular organisms, certain proteins function in cell-to-cell recognition and signaling. For example, hormones such as insulin are secreted by endocrine cells and bind to the insulin receptor protein found within the plasma membrane of target cells.
- **Enzymes,** which accelerate chemical reactions, are a particularly important category of proteins. Some enzymes play a role in the breakdown of molecules or macromolecules into smaller units. These enzymes are important in the utilization of energy.

Molecular biologists have come to realize that the functions of proteins underlie the cellular characteristics of every organism. At the molecular level, proteins can be viewed as the active participants in the enterprise of life.

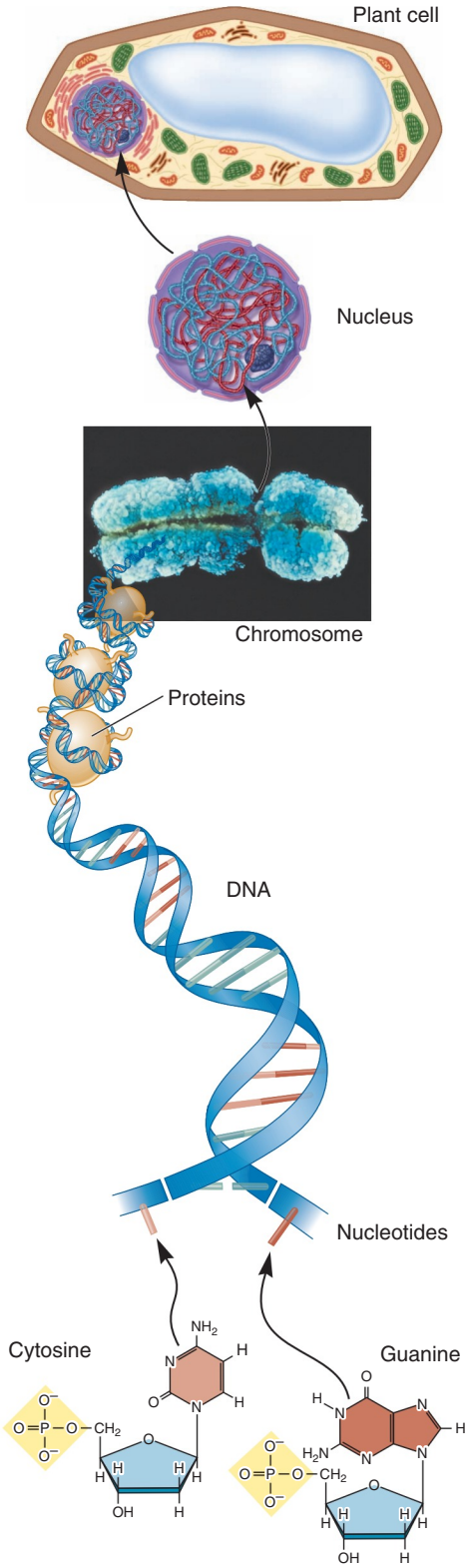


FIGURE 1.4 Molecular organization of a living cell. Cellular structures are constructed from smaller building blocks. In this example, DNA is formed from the linkage of nucleotides to produce a very long macromolecule. The DNA associates with proteins to form a chromosome. The chromosomes are located within a membrane-bound organelle called the nucleus, which, along with many different types of organelles, is found within a complete cell.

Concept Check: Is DNA a small molecule, a macromolecule, or an organelle?

DNA Stores the Information for Protein Synthesis

As mentioned, the genetic material of living organisms is composed of a substance called deoxyribonucleic acid, abbreviated DNA. The DNA stores the information needed for the synthesis of all proteins. In other words, the main function of the genetic blueprint is to code for the production of proteins in the correct cell, at the proper time, and in suitable amounts. This task is extremely complicated because living cells make thousands of different proteins. Genetic analyses have shown that a typical bacterium can make a few thousand different proteins, and estimates among higher eukaryotes range in the tens of thousands.

DNA's ability to store information is based on its structure.

- DNA is composed of a linear sequence of **nucleotides,** each of which contains one of four nitrogen-containing bases: adenine (A), thymine (T), guanine (G), or cytosine (C).
- The linear order of these bases along a DNA molecule contains information similar to the way that groups of letters of the alphabet represent words. For example, the "meaning" of the sequence of bases ATGGGCCTTAGC differs from that of TTTAAGCTTGCC.
- DNA sequences within most genes contain the information to direct the order of amino acids within **polypeptides** according to the **genetic code.** In the code, a three-base sequence specifies one particular **amino acid** among the 20 possible choices.
- The sequence of amino acids in a polypeptide cause it to fold into a particular structure; one or more polypeptides form a functional protein.

In this way, the DNA can store the information to specify the proteins made by an organism.

DNA Sequence	Amino Acid Sequence
ATG GGC CTT AGC	Methionine Glycine Leucine Serine
TTT AAG CTT GCC	Phenylalanine Lysine Leucine Alanine

In living cells, DNA is found within large structures known as **chromosomes.** Figure 1.5 is a micrograph of the 46 chromosomes in a cell from a human male, which are found in pairs. The DNA of an average human chromosome is an extraordinarily long, linear, double-stranded structure that contains well over a hundred million nucleotides. Along the immense length of a chromosome, the genetic information is parceled into functional units known as genes. An average-sized human chromosome is expected to carry about 1000 different genes.

The Information in DNA Is Accessed During the Process of Gene Expression

To synthesize its proteins, a cell must be able to access the information that is stored within its DNA. The process of using a gene sequence to affect the characteristics of cells and organisms is

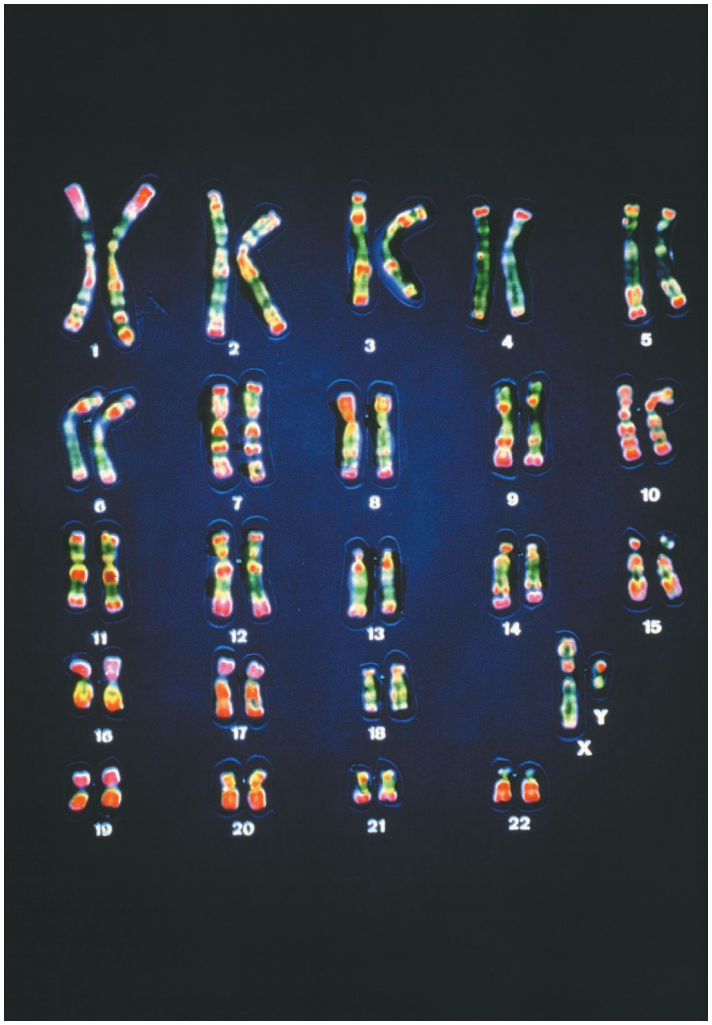
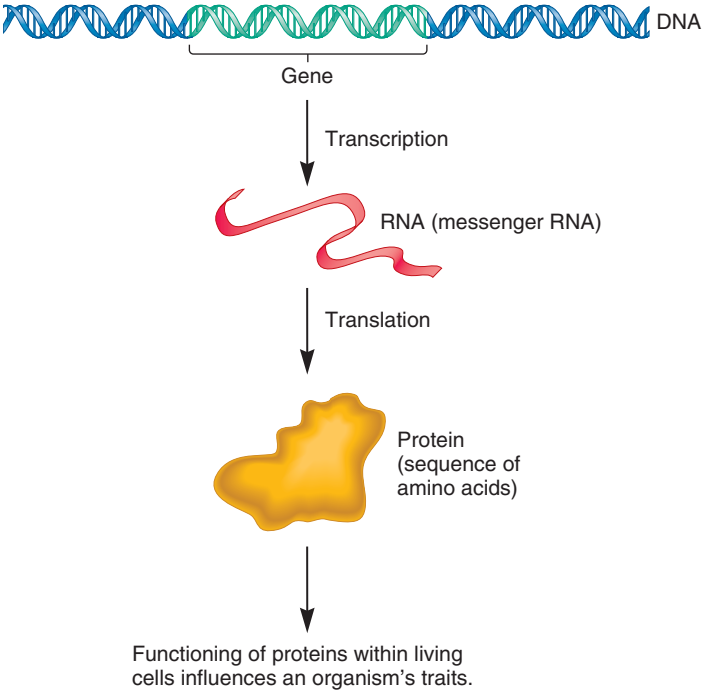


FIGURE 1.5 A micrograph of the 46 chromosomes found in a cell from a human male.

Concept Check: Which types of macromolecules are found in chromosomes?

referred to as **gene expression.** At the molecular level, the information is accessed in a stepwise process (**Figure 1.6**).

1. In the first step, known as **transcription,** the DNA sequence within a gene is copied into a nucleotide sequence of **ribonucleic acid (RNA).** Most genes encode RNAs that contain the information for the synthesis of a particular polypeptide. This type of RNA is called **messenger RNA (mRNA).**
2. During the process of **translation,** the sequence of nucleotides in an mRNA provides the information (using the genetic code) to produce the amino acid sequence of a polypeptide.
3. A polypeptide folds into a three-dimensional structure. As mentioned, a protein is a functional unit. Some proteins are composed of a single polypeptide, and other proteins consist of two or more polypeptides.
4. The functioning of proteins contributes to cell structure and function.



ONLINE ANIMATION

FIGURE 1.6 Gene expression at the molecular level. The expression of a gene is a multistep process. During transcription, one of the DNA strands is used as a template to make an RNA strand. During translation, the RNA strand is used to specify the sequence of amino acids within a polypeptide. One or more polypeptides produce a functional protein, thereby influencing an organism's traits.

Concept Check: Where is the information to make a polypeptide stored?

1.1 REVIEWING THE KEY CONCEPTS

- Living cells are composed of nucleic acids (DNA and RNA), proteins, carbohydrates, and lipids. The proteome largely determines the structure and function of cells (see Figure 1.4).
- DNA, which is found within chromosomes, stores the information to make proteins (see Figure 1.5).
- Most genes encode polypeptides that are units within functional proteins. Gene expression at the molecular level involves transcription to produce mRNA and translation to produce a polypeptide (see Figure 1.6).

1.1 COMPREHENSION QUESTIONS

1. Which of the following is *not* a constituent of a cell's proteome?
   a. An enzyme
   b. A motor protein
   c. A receptor in the plasma membrane
   d. An mRNA
2. A gene is a segment of DNA that has the information to produce a functional product. The functional product of most genes is
   a. DNA.
   b. mRNA.
   c. a polypeptide.
   d. All of the above.

3. The function of the genetic code is to
   a. promote transcription.
   b. specify the amino acids within a polypeptide.
   c. alter the sequence of DNA.
   d. None of the above.
4. The process of transcription directly results in the synthesis of
   a. DNA.
   b. RNA.
   c. a polypeptide.
   d. All of the above.

1.2 THE RELATIONSHIP BETWEEN GENES AND TRAITS

Learning Outcomes:

1. Explain how the expression of genes leads to an organism's traits.
2. Define *genetic variation.*
3. Discuss the relationship between genes, traits, and the environment.
4. Describe how genes are transmitted in sexually reproducing species.
5. Outline the process of evolution.

A trait is any characteristic that an organism displays. In genetics, we can place traits into different categories.

- **Morphological traits** affect the appearance, form, and structure of an organism. The color of a flower and the height of a pea plant are morphological traits. Geneticists frequently study these types of traits because they are easy to evaluate. For example, an experimenter can simply look at a plant and tell if it has red or white flowers.
- **Physiological traits** affect the ability of an organism to function. For example, the rate at which a bacterium metabolizes a sugar such as lactose is a physiological trait. Like morphological traits, physiological traits are controlled, in part, by the expression of genes.
- **Behavioral traits** affect the ways an organism responds to its environment. An example is the mating calls of bird species. In animals, the nervous system plays a key role in governing such traits.

In this section, we will examine the relationship between the expression of genes and an organism's traits.

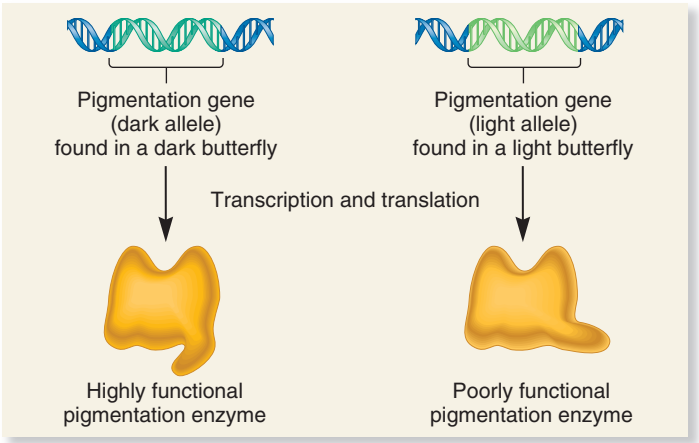
The Molecular Expression of Genes Within Cells Leads to an Organism's Traits

A complicated, yet very exciting, aspect of genetics is that our observations and theories span four levels of biological organization: molecules, cells, organisms, and populations. This can make it difficult to appreciate the relationship between genes and traits. To understand this connection, we need to relate the following four phenomena:

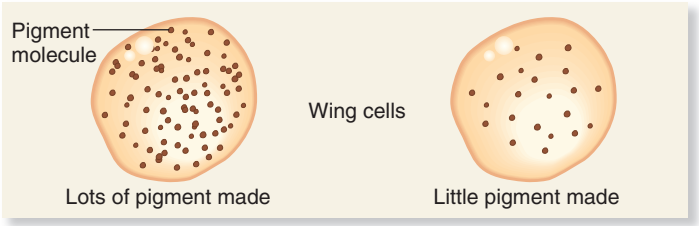
1. As we learned in Section 1.1, genes are expressed at the **molecular level.** In other words, gene transcription and translation lead to the production of a particular protein, which is a molecular process.
2. Proteins often function at the **cellular level.** The function of a protein within a cell affects the structure and workings of that cell.
3. An organism's traits are determined by the characteristics of its cells. We do not have microscopic vision, yet when we view morphological traits, we are really observing the properties of an individual's cells. For example, a red flower has its color because the flower cells make a red pigment. The trait of red flower color is an observation at the **organism level,** yet the trait is rooted in the molecular characteristics of the organism's cells.
4. A **species** is a group of organisms that maintains a distinctive set of attributes in nature. The occurrence of a trait within a species is an observation at the **population level.** Along with learning how a trait occurs, we also want to understand why a trait becomes prevalent in a particular species. In many cases, researchers discover that a trait predominates within a population because it promotes the reproductive success of the members of the population.

As a schematic example to illustrate the four levels of genetics, **Figure 1.7** shows the trait of pigmentation in butterflies. One is light-colored and the other is very dark. Let's consider how we can explain this trait at the molecular, cellular, organism, and population levels.

1. At the molecular level, we need to understand the nature of the gene or genes that govern this trait. As shown in Figure 1.7a, a gene, which we will call the pigmentation gene, is responsible for the amount of pigment produced. The pigmentation gene can exist in two different forms called **alleles.** In this example, one allele confers a dark pigmentation and one causes a light pigmentation. Each of these alleles encodes a protein that functions as a pigment-synthesizing enzyme. However, the DNA sequences of the two alleles differ slightly from each other. This difference in the DNA sequence leads to a variation in the structure and function of the respective pigmentation enzymes.
2. At the cellular level (Figure 1.7b), the functional differences between the pigmentation enzymes affect the amount of pigment produced. The allele causing dark pigmentation, which is shown on the left, encodes a protein that functions very well. Therefore, when this gene is expressed in the cells of the wings, a large amount of pigment is made. By comparison, the allele causing light pigmentation encodes an enzyme that functions poorly. Therefore, when this allele is the only pigmentation gene expressed, little pigment is made.

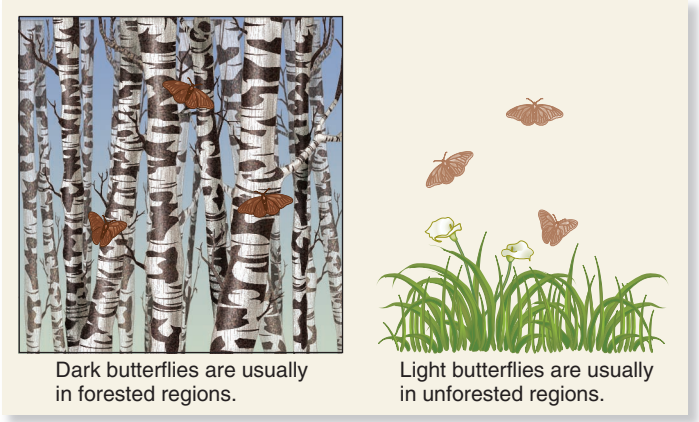


(a) Molecular level



(b) Cellular level

(c) Organism level



(d) Population level

FIGURE 1.7 The relationship between genes and traits at the (a) molecular, (b) cellular, (c) organism, and (d) population levels.

Concept Check: Which butterfly has a more active pigment-producing enzyme, the light- or dark-colored one?

3. At the organism level (Figure 1.7c), the amount of pigment in the wing cells governs the color of the wings. If the pigment cells produce high amounts of pigment, the wings are dark-colored; if the pigment cells produce little pigment, the wings are light.
4. Finally, at the population level (Figure 1.7d), geneticists want to know why a species of butterfly has some members with dark wings and others with light wings. One possible explanation is differential predation. The butterflies with dark wings might avoid being eaten by birds if they happen to live within the dim light of a forest. The dark wings help to camouflage the butterfly if it were perched on a dark surface such as a tree trunk. In contrast, the light-colored wings would be an advantage if the butterfly inhabited a brightly lit meadow. Under these conditions, a bird may be less likely to notice a light-colored butterfly that is perched on a sunlit surface. A geneticist might study this species of butterfly and find that the dark-colored members usually live in forested areas and the light-colored members reside in unforested regions.

Inherited Differences in Traits Are Due to Genetic Variation

In Figure 1.7, we considered how gene expression can lead to variation in a trait of an organism, such as dark- versus light-colored butterflies. Variation in traits among members of the same species is very common. For example, some people have black hair, and others have brown hair; some petunias have white flowers, but others have purple flowers. These are examples of **genetic variation.** This term describes the differences in inherited traits among individuals within a population.

In large populations that occupy a wide geographic range, genetic variation can be quite striking. In fact, morphological differences have often led geneticists to misidentify two members of the same species as belonging to separate species. As an example, **Figure 1.8** shows two dyeing poison frogs that are members of the same species, *Dendrobates tinctorius.* They display dramatic differences in their markings. Such contrasting forms within a single species are termed **morphs.** You can easily imagine how someone might mistakenly conclude that these frogs are not members of the same species.

Changes in the nucleotide sequence of DNA underlie the genetic variation that we see among individuals. Throughout this textbook, we will routinely examine how variation in the genetic material results in changes in the outcome of traits. At the molecular level, genetic variation can be attributed to different types of modifications.

- Small or large differences can occur within gene sequences. When such changes initially occur, they are called **gene mutations,** which are heritable changes in the genetic material. Gene mutations result in genetic variation in which a gene is found in two or more alleles, as previously described in Figure 1.7. In many cases, gene mutations alter the expression or function of the protein that the gene specifies.

FIGURE 1.8 Two dyeing poison frogs (*Dendrobates tinctorius*) showing different morphs within a single species.

Concept Check: Why do these two frogs look so different?

(a) (b)

FIGURE 1.9 Examples of chromosome variation. (a) A person with Down syndrome competing in the Special Olympics. This person has 47 chromosomes rather than the common number of 46, because she has an extra copy of chromosome 21. **(b)** A wheat plant. Bread wheat is derived from the contributions of three related species with two sets of chromosomes each, producing an organism with six sets of chromosomes.

Concept Check: Are these examples of gene mutations, variation in chromosome structure, or variation in chromosome number?

- Major alterations can also occur in the structure of a chromosome. A large segment of a chromosome can be lost, rearranged, or reattached to another chromosome.
- Variation may also occur in the total number of chromosomes. In some cases, an organism may inherit one too many or one too few chromosomes. In other cases, it may inherit an extra set of chromosomes.

Variations within the sequences of genes are a common source of genetic variation among members of the same species. In humans, familiar examples of variation involve genes for eye color, hair texture, and skin pigmentation. Chromosome variation—a change in chromosome structure or number (or both)—is also found, but this type of change is often detrimental. Many human genetic disorders are the result of chromosomal alterations. An example is Down syndrome, which is due to the presence of an extra chromosome (**Figure 1.9a**). By comparison, chromosome variation in plants is common and often can lead to plants with superior characteristics, such as increased resistance to disease. Plant breeders have frequently exploited this observation. Cultivated varieties of wheat, for example, have many more chromosomes than the wild species (**Figure 1.9b**).

Traits Are Governed by Genes and by the Environment

In our discussion thus far, we have considered the role that genes play in the outcome of traits. Another critical factor is the **environment**—the surroundings in which an organism exists. A variety of factors in an organism's environment profoundly affect its morphological and physiological features. For example, a person's diet greatly influences many traits such as height, weight, and even intelligence. Likewise, the amount of sunlight a plant receives affects its growth rate and the color of its flowers. The term **norm of reaction** refers to the effects of environmental variation on an individual's traits.

External influences may dictate the way that genetic variation is manifested in an individual. An interesting example is the human genetic disease **phenylketonuria (PKU).** Humans have a gene that encodes an enzyme known as phenylalanine hydroxylase. Most people have two functional copies of this gene. People with one or two functional copies of the gene can eat foods containing the amino acid phenylalanine and metabolize it properly.