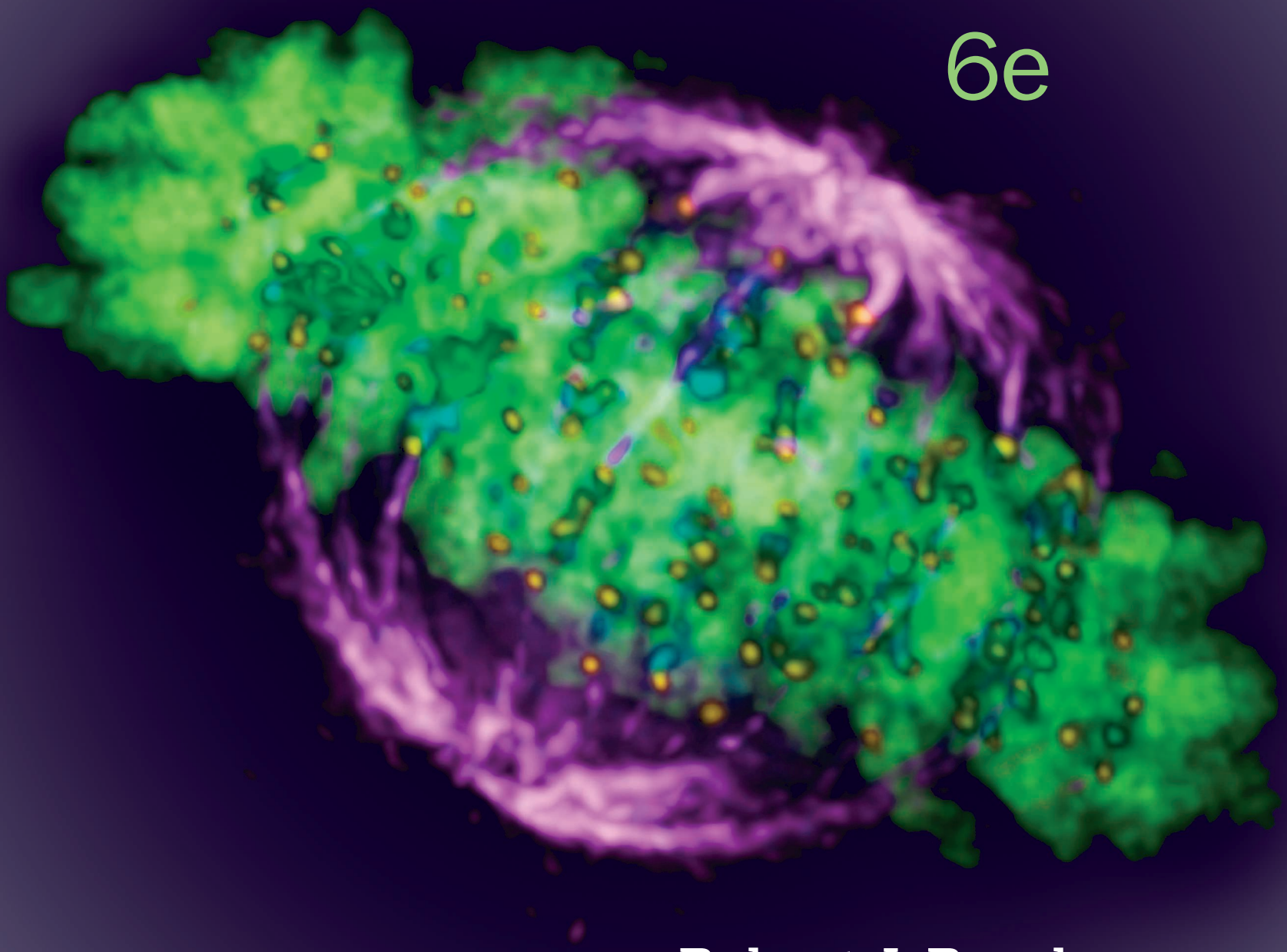
GENETICS

ANALYSIS & PRINCIPLES

6e



Robert J. Brooker

Mc Graw Hill Education

GENETICS

ANALYSIS & PRINCIPLES

GENETICS

ANALYSIS & PRINCIPLES

Sixth Edition

ROBERT J. BROOKER

University of Minnesota

Mc Graw Hill Education

GENETICS: ANALYSIS & PRINCIPLES, SIXTH EDITION

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI/LWI 21 20 19 18 17

ISBN 978–1–259–61602-0
MHID 1–259–61602–9

Senior Vice President, Products & Markets: *G. Scott Virkler*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Production & Technology Services: *Betsy Whalen*
Director of Digital Content: *Michael G. Koot, PhD*
Brand Manager: *Justin K. Wyatt, PhD*
Director of Development, Biology: *Elizabeth M. Sievers*
Digital Product Analyst: *Christine Carlson*
Market Development Manager: *Michelle Bradin*
Executive Marketing Manager: *Patrick E. Reidy*
Project Manager: *Angie FitzPatrick*
Content Project Managers: *Jayne Klein/Christina Nelson*
Senior Buyer: *Sandy Ludovissy*
Senior Designer: *David W. Hash*
Cover Image: © *Dr. Paul Andrews, University of Dundee/Science Photo Library/Getty Images*
Content Licensing Specialists: *Carrie Burger/Shannon Manderscheid*
Compositor: *Aptara, Inc.*
Typeface: *STIX MathJax Main*
Printer: *LSC Communications*

Library of Congress Cataloging-in-Publication Data

Names: Brooker, Robert J.
Title: Genetics : analysis & principles / Robert J. Brooker, University of Minnesota.
Description: Sixth edition. | New York NY : McGraw-Hill Education, [2018] |
Includes index.
Identifiers: LCCN 2016034541| ISBN 9781259616020 (alk. paper) | ISBN 1259616029 (alk. paper)
Subjects: LCSH: Genetics.
Classification: LCC QH430 .B766 2018 | DDC 576.5--dc23 LC record available at https://lccn.loc.gov/2016034541

2013035482

BRIEF CONTENTS

TABLE OF CONTENTS

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 continued to work on transporters at the University of Minnesota with an emphasis on the structure, function, and regulation of iron transporters found in bacteria and *C. elegans*. At the University of Minnesota, he teaches undergraduate courses in biology and genetics.

DEDICATION

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

PREFACE

In the sixth edition of *Genetics: Analysis & Principles*, the content has been updated to reflect current trends in the field. In addition, the presentation of the content has been improved in a way that fosters active learning. 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 sixth edition of *Genetics: Analysis & Principles* a fun learning tool.

Overall, an effective textbook needs to accomplish four 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. Third, an effective textbook should have pedagogical features, such as formative assessment, that foster student learning. And finally, it should inspire students so they want to pursue that field as a career. The hard work that has gone into the sixth edition of *Genetics: Analysis & Principles* has been aimed at achieving all four of these goals!

FLIPPING THE CLASSROOM

A 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 outside 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 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 each student understand if his or her 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 on 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 less time to teach and therefore will cover 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, *Genetics: Analysis & Principles*, Sixth Edition, is intended to provide students with a resource that can be effectively used outside of the classroom. Here are several of the key pedagogical features:

- ***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***nformaiton that is available to the student. Finally, the student is guided through one or more ***P***roblem-Solving ***S***trategies to tackle the question.

GENETIC TIPS **THE QUESTION:** All of the Genetic TIPS begin with a question. As an example, let's consider the following question:

The coding strand of DNA in a segment of a gene is as follows: ATG GGC CTT AGC. This strand carries the information to make a region of a polypeptide with the amino acid sequence, methionine-glycine-leucine-serine. What would be the consequences if a mutation changed the second cytosine (C) in this sequence to an adenine (A)?

TOPIC: ***What topic in genetics does this question address?*** The topic is gene expression. More specifically, the question is about the relationship between a gene sequence and the genetic code.

INFORMATION: ***What information do you know based on the question and your understanding of the topic?*** In the question, you are given the base sequence of a short segment of a gene and told that one of the bases has been changed. From your understanding of the topic, you may remember that a polypeptide sequence is determined by reading the mRNA (transcribed from a gene) in groups of three bases called codons.

PROBLEM-SOLVING STRATEGY: ***Compare and contrast.*** One strategy to solve this problem is to compare the mRNA sequence (transcribed from this gene) before and after the mutation:

Original: AUG GGC **C**UU AGC

Mutant: AUG GGC **A**UU AGC

ANSWER: The mutation has changed the sequence of bases in the mRNA so that the third codon has changed from CUU to AUU. Because codons specify amino acids, this may change the third amino acid to something else. Note: If you look ahead to Chapter 13 (see Table 13.1), you will see that CUU specifies leucine, whereas AUU specifies isoleucine. Therefore, you would predict that the mutation would change the third amino acid from leucine to isoleucine.

- **Genes → Traits:** Because genetics is such a broad discipline, ranging from the molecular level to populations, many instructors have told us that it is a challenge for students to see both "the forest and the trees." It is commonly mentioned that students often have trouble connecting the concepts they have learned in molecular genetics with the traits that occur at the level of a whole organism (i.e., What does transcription have to do with blue eyes?). To try to make this connection more meaningful, certain figure legends in each chapter, designated **Genes → Traits,** remind students that molecular and cellular phenomena ultimately lead to the traits that are observed in each species (see Figure 14.8).
- **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 once 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 regularly given formative assessment so they can gauge whether they are mastering the material. Formative assessment is a major feature of this textbook and is bolstered by Connect—a state-of-the art digital assignment and assessment platform. In *Genetics: Analysis & Principles*, Sixth Edition, formative assessment is provided in multiple ways.

  1. As mentioned, a new feature called Genetic TIPS is aimed at helping students refine their problem solving skills.
  2. Each section of every chapter ends with multiple-choice questions. Also, compared with the previous edition, many chapters in the sixth edition are divided into more sections that 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.
  3. Most figures have Concept Check questions so students can determine if they understand the key points in the figure.
  4. Extensive end-of chapter questions continue to provide students with feedback regarding their mastery of the material.
  5. The textbook material is supported by digital learning tools found in Connect. Questions and activities are assignable in Connect, and students also have access to our valuable adaptive study tool, SmartBook. With this tool, students are repeatedly given questions regarding the textbook material, and depending on their answers, they may advance ahead in their reading, or they are given specific advice on what textbook material to go back and review.

Overall, the pedagogy of *Genetics: Analysis & Principles*, sixth edition, has been designed to foster student learning. Instead of being a collection of facts and figures, *Genetics: Analysis & Principles*, Sixth Edition, by Rob 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!

SIGNIFICANT CONTENT CHANGES IN THE SIXTH EDITION

- ***NEW!*** A new problem-solving feature called Genetic TIPS has been added to the sixth edition. The Genetic TIPS are found within each chapter and three or four are found at the end of each chapter.
- ***NEW!*** The topic of Epigenetics has been expanded to a whole chapter, which is now Chapter 16.
- ***NEW!*** A new chapter on non-coding RNA has been added, which is Chapter 17. This long-overdue chapter is in response to a remarkable explosion in our appreciation for the roles of non-coding RNAs in many aspects of molecular biology. Note: Although two new chapters have been added to this edition, the overall page length of the sixth edition is not longer than the fifth edition.
- ***NEW!*** CRISPR-Cas systems: The role of the CRISPR-Cas system in providing prokaryotes with a genome defense mechanism is described in Chapter 17, and its use by researchers to mutate genes is described in Chapter 21.

Examples of Specific Content Changes to Individual Chapters

- Chapter 2. Mendelian Inheritance: Several Genetic TIPS have been added to help students work through problem-solving strategies involving Mendelian inheritance.
- Chapter 3. Chromosome Transmission During Cell Division and Sexual Reproduction: The discussion of the random alignment of homologs during metaphase of meiosis I was expanded.
- Chapter 4. Extensions of Mendelian Inheritance: The topic of gene interaction was streamlined to focus primarily on examples in which the underlying molecular mechanisms are known.
- Chapter 5. Non-Mendelian Inheritance:A common misconception among students is that you can use a Punnett square to deduce nonMendelian inheritance patterns. Throughout the chapter, this misconception has been laid to rest, and students are given effective strategies to predict offspring genotypes and phenotypes.
- Chapter 6. Genetic and Linkage Mapping in Eukaryotes: When looking at experiments involving linkage, student often find it very difficult to identify the recombinant offspring. In various parts of the chapter, a strong effort has been made to make it clear that recombinant offspring have inherited a chromosome that is the product of a crossover. Along these same lines, a new figure (see Figure 6.6) has been added involving the experiments of Curt Stern showing that recombinant offspring carry chromosomes that are the product of a crossover. Also, Figure 6.8 has been revised to emphasis this point.
- Chapter 7. Genetic Transfer and Mapping in Bacteria: Figure 7.13 is a new figure showing the increase in methicillin resistance in certain *Staphylococcus aureus* strains.

- Chapter 8. Variation in Chromosome Structure and Number: Several Genetic TIPS have been added to help students solve problems that involve changes in chromosome structure and chromosome number.
- Chapter 9. Molecular Structure of DNA and RNA: The section on the discovery of the DNA double helix has been streamlined to focus on the key experiments.
- Chapter 10. Chromosome Organization and Molecular Structure: The topic of bacterial chromosome structure has been updated, which includes a new figure (see Figure 10.3) and a discussion of microdomains.
- Chapter 11. DNA Replication: A new figure has been added on the initiation of DNA replication in eukaryotes (see Figure 11.20).
- Chapter 12. Gene Transcription and RNA Modification: The information on alternative splicing has been moved to this chapter.
- Chapter 13. Translation of mRNA: Several Genetic TIPS have been added to help students understand the relationship between the genetic code and the synthesis of polypeptides.
- Chapter 14. Gene Regulation in Bacteria: The information on catabolite activator protein has been updated.
- Chapter 15. Gene Regulation in Eukaryotes I: Transcriptional and Translation Regulation: The material on eukaryotic gene regulation is now divided into two chapters. Chapter 15 focuses on transcriptional and translational regulation.
- Chapter 16. Gene Regulation in Eukaryotes II: Epigenetics: This topic has now been expanded to an entire chapter. A new subsection has been added on the role of epigenetics in vernalization, which is the process in which some plant species require an exposure to cold in order to flower the following spring. Also, a new section has been added on the intriguing topic of paramutation.
- Chapter 17. Non-coding RNA: This new chapter begins with an overview of the general functions of non-coding RNAs, and then the subsequent sections explore certain topics in greater detail, such as their role in chromatin modification, transcription, translation, protein targeting, and genome defense (e.g., the CRISPR-Cas system).
- Chapter 18. Genetics of Viruses: The material on the integration of phage λ has been added to this chapter, along with a brief discussion of Zika virus. Also, information on the origin of HIV and the occurrence of HIV infection worldwide and in the US has been updated.
- Chapter 19. Gene Mutation and DNA Repair: The information on the mismatch repair system has been updated.
- Chapter 20. Recombination, Immunogenetics, and Transposition: Section 20.2 has been revised to focus on immunogenetics.
- Chapter 21. DNA Technologies: A new subsection has been added on gene mutagenesis, which includes a description of the Crispr-Cas system for inactivating and mutating genes.
- Chapter 22. Biotechnology: Several Genetic TIPS have been added to help students appreciate the uses of molecular techniques in biotechnology.
- Chapter 23. Genomics I: Analysis of DNA: The information has been updated regarding completed genome sequences and other aspects of genomics.
- Chapter 24. Genomics II: Functional Genomics, Proteomics, and Bioinformatics: A new subsection has been added on the method called RNA-Seq (see Figure 24.3). The Bioinformatics section has been reorganized with an emphasis on gene prediction and homology.
- Chapter 25. Medical Genetics and Cancer: Several Genetic TIPS have been added to help students understand how mutations play a role in certain diseases, including cancer.
- Chapter 26. Developmental Genetics: The information on *Hox* genes in development, and the role of the *SRY* gene is human sex determination, have been updated.
- Chapter 27. Population Genetics: The topic of inbreeding has been expanded.
- Chapter 28. Complex and Quantitative Traits: The topic of the identification of QTLs is now found in its own subsection.
- Chapter 29. Evolutionary Genetics: The cladistics method for constructing a phylogenetic tree is compared with the UPGMA method.

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
612-624-3053

Mc Graw Hill Education

connect®

Required=Results

©Getty Images/iStockphoto

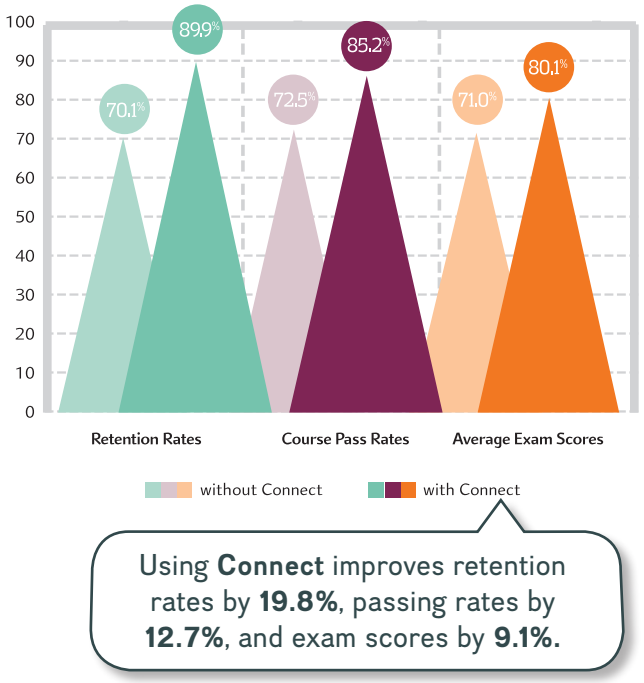
McGraw-Hill Connect®
Learn Without Limits

Connect is a teaching and learning platform that is proven to deliver better results for students and instructors.

Connect empowers students by continually adapting to deliver precisely what they need, when they need it, and how they need it, so your class time is more engaging and effective.

73% of instructors who use **Connect** require it; instructor satisfaction **increases** by 28% when **Connect** is required.

Connect's Impact on Retention Rates, Pass Rates, and Average Exam Scores



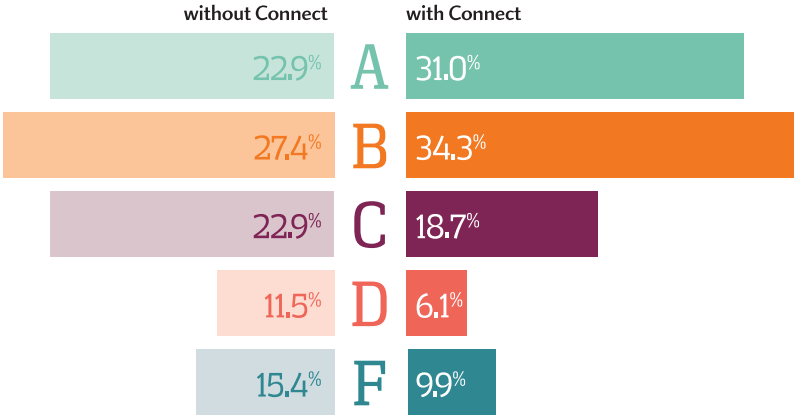
Using **Connect** improves retention rates by **19.8%**, passing rates by **12.7%**, and exam scores by **9.1%.**

Analytics

Connect Insight®

Connect Insight is Connect's new one-of-a-kind visual analytics dashboard that provides at-a-glance information regarding student performance, which is immediately actionable. By presenting assignment, assessment, and topical performance results together with a time metric that is easily visible for aggregate or individual results, Connect Insight gives the user the ability to take a just-in-time approach to teaching and learning, which was never before available. Connect Insight presents data that helps instructors improve class performance in a way that is efficient and effective.

Impact on Final Course Grade Distribution



Adaptive

THE **ADAPTIVE READING EXPERIENCE** DESIGNED TO TRANSFORM THE WAY STUDENTS READ

More students earn **A's** and **B's** when they use McGraw-Hill Education **Adaptive** products.

SmartBook®

Proven to help students improve grades and study more efficiently, SmartBook contains the same content within the print book, but actively tailors that content to the needs of the individual. SmartBook's adaptive technology provides precise, personalized instruction on what the student should do next, guiding the student to master and remember key concepts, targeting gaps in knowledge and offering customized feedback, and driving the student toward comprehension and retention of the subject matter. Available on tablets, SmartBook puts learning at the student's fingertips—anywhere, anytime.

Over **8 billion questions** have been answered, making McGraw-Hill Education products more intelligent, reliable, and precise.

www.mheducation.com

STUDENTS WANT SMARTBOOK®

- **95%** of students reported **SmartBook** to be a more effective way of reading material.
- **100%** of students want to use the Practice Quiz feature available within **SmartBook** to help them study.
- **100%** of students reported having reliable access to off-campus wifi.
- **90%** of students say they would purchase **SmartBook** over print alone.
- **95%** of students reported that **SmartBook** would impact their study skills in a positive way.

*Findings based on 2015 focus group results administered by McGraw-Hill Education

Mc Graw Hill Education

ACKNOWLEDGMENTS

The production of a textbook is truly a collaborative effort, and I am deeply indebted to many people. All six editions of this textbook went 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.

Deborah Brooker (Freelance Developmental Editor) meticulously read the new material, analyzed every figure, and offered extensive feedback. Her attention to detail in this edition and previous editions has profoundly contributed to the accuracy and clarity of this textbook. I would also like to thank Jane Hoover (Freelance Copy Editor) for understanding the material and working extremely hard to improve the text's clarity. Her efforts are truly appreciated.

I would particularly like to acknowledge the many people at McGraw-Hill Education whose skills and insights are amazing. My highest praise goes to Elizabeth Sievers (Lead Product Developer), who carefully checks all aspects of textbook development and makes sure that all of the pieces of the puzzle are in place. I am also grateful to Justin Wyatt (Brand Manager) for overseeing this project. I would like to thank other people at McGraw-Hill who have played key roles in producing an actual book and the supplements that go along with it. In particular, Jayne Klein (Senior 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 Carrie Burger (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 created an awesome cover. Finally, I would like to thank Patrick Reidy (Executive Marketing Manager), whose major efforts begin when the sixth edition comes out!

I would also like to extend my thanks to everyone at Aptara who 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 the sixth edition.

Finally, I want to thank the many scientists who reviewed the chapters of this textbook with special attention to the new Chapter 17, Non-coding RNAs. Their broad insights and constructive suggestions were an overriding factor that shaped its final content and organization. I am truly grateful for their time and compassion.

- Susan Carpenter *University of California, Santa Cruz*
- Johnny El-Rady *University of South Florida*
- Terri McElhinny *Michigan State University*
- Douglas Wendell *Oakland University*
- Jeremy Wilusz *University of Pennsylvania Perelman School of Medicine*

REVIEWERS

Previous editions

Amy Abdulovic-Cui, *Augusta State University*
Steve Alas, *California State Polytechnic University, Pomona*
Harvey Babich, *Stern College for Women*
Laura Hill Bermingham, *University of Vermont*
Hector Biliran Jr., *Xavier University of Louisiana*
Mirjana Milosevic Brockett, *Georgia Institute of Technology*
Madhusudan Choudhary, *Sam Houston State University*
Reggie Cobb, *Nash Community College*
Dan Choffnes, *Carthage College*
Laurie Cotroneo, *Southern Utah University*
Robert S. Dotson, *Tulane University*
Robert Hinrichsen, *Indiana University of Pennsylvania*
Margaret Hollingsworth, *University at Buffalo*
Mitrick Johns, *Illinois University*
Ekaterina Kaverina, *East Tennessee State University*
Jesse Mager, *University of Massachusetts*
Norah R. McCabe, *Washington State University*
R. Deborah Overath, *Texas A&M University–Corpus Christi*
Thomas Peavy, *California State University–Sacramento*
Rongsun Pu, *Kean University*
Robert Rutledge, *DeSales University*
Julian Shull, *Appalachian State University*
Jeffry Shultz, *Louisiana Tech University*
Ronald Wagner, *Central Washington University*
Carey Waldburger, *William Paterson University*
Gary L. Walker, *Appalachian State University*
Jessica Wooten, *The University of Findlay*

CHAPTER OUTLINE

CC (for "carbon copy" or "copy cat"), the first cloned pet. *In 2002, the cat shown here was produced by cloning, a procedure described in Chapter 22.*

1 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 DNA found within all of our chromosomes (**Figure 1.1**). Remarkably, in only a decade, they determined the DNA sequence (the order of the bases A, T, G, and C) of over 90% of the human genome. The completed sequence, published in 2003, has an accuracy greater than 99.99%; less than one mistake was made in every 10,000 base pairs!

In 2008, a more massive undertaking, called the 1000 Genomes Project, was launched to establish a detailed understanding of human genetic variation. In this international project, researchers set out to determine the DNA sequence of at least 1000 anonymous participants from around the globe. In 2015, the sequencing of over 2500 genomes was described in the journal *Nature*.

Studying the human genome allows us to explore fundamental details about ourselves at the molecular level. The results of the Human Genome Project and the 1000 Genomes Project have shed considerable light on basic questions, like 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 leading to 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. For example, researchers have developed genetic techniques to produce medicines, such as human insulin, that would otherwise be difficult or impossible to make. Human insulin is synthesized in strains of *Escherichia coli* bacteria that have been genetically altered by the addition of genes that encode the polypeptides that form this hormone. The bacteria are grown in a laboratory and make large amounts of human insulin. As discussed in Chapter 22, the insulin is purified and administered to many people with insulin-dependent diabetes.

DNA, the molecule of life

The adult human body is composed of trillions of cells.

Most human cells contain the following:

- 46 human chromosomes, found in 23 pairs
- 2 meters of DNA
- Approximately 22,000 genes coding for proteins that perform most life functions
- Approximately 3 billion DNA base pairs per set of chromosomes, containing the bases A, T, G, and C

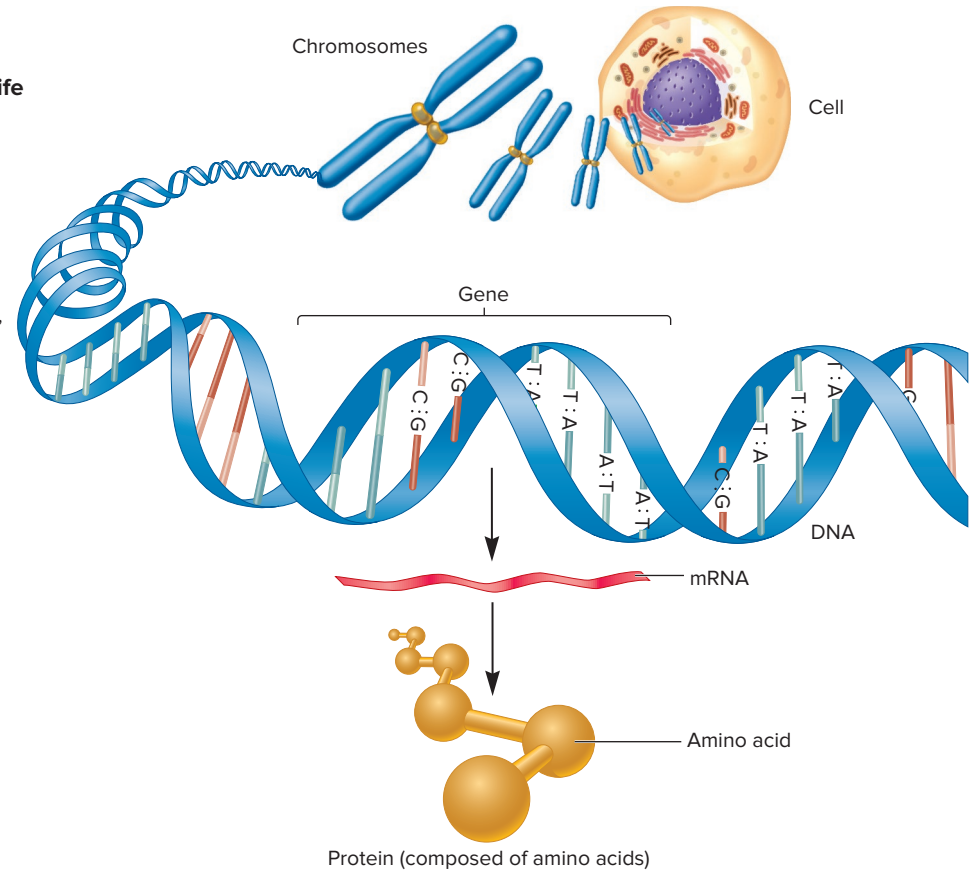


FIGURE 1.1 The human genome. The human genome is a complete set of human chromosomes. People have two sets of chromosomes—one set from each parent—which are found in the cell nucleus. The Human Genome Project revealed that each set of chromosomes is composed of a DNA sequence that is approximately 3 billion nucleotide base pairs long. Estimates suggest that each set contains about 22,000 different genes that encode proteins. As discussed later, most genes are first transcribed into mRNA and then the mRNA is used to make proteins. 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.

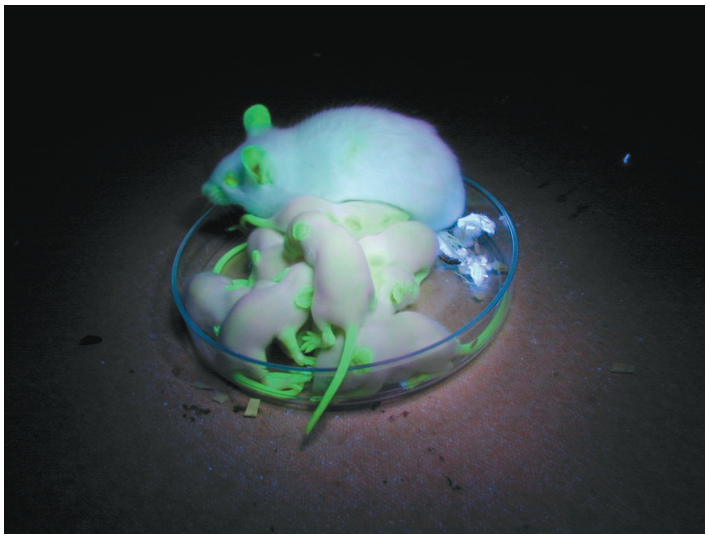
CONCEPT CHECK: How might a better understanding of our genes be used in the field of medicine?

New genetic technologies are often met with skepticism and sometimes even with disdain. An example is mammalian cloning. In 1997, Ian Wilmut and his colleagues created 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 CC (for "carbon copy" or "copy cat"; see photo at the beginning of the chapter). The cloning of mammals provides the potential for many practical applications. With regard to livestock, cloning 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. This prospect has raised serious ethical questions. Within the past few years, legislation has been introduced that involves bans on human cloning.

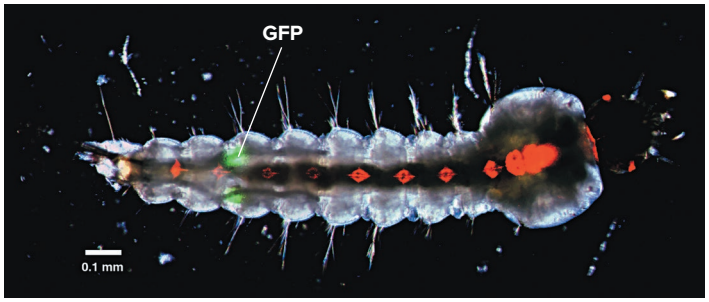
Finally, genetic technologies provide the means to modify the traits of animals and plants in ways that would have been unimaginable just a few decades ago. **Figure 1.3a** illustrates a striking example in which scientists introduced a gene from

FIGURE 1.2 The cloning of a mammal. The lamb in the front is Dolly, the first mammal to be cloned. She was cloned from the cells of a Finn Dorset (a white-faced sheep). The sheep in the back is Dolly's surrogate mother, a Blackface ewe. A description of how Dolly was produced is presented in Chapter 22.

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 jellyfish encodes a protein called green fluorescent protein (GFP). The *GFP* gene was cloned and introduced into mice. When these mice are exposed to UV light, GFP emits a bright green color. These mice glow green, just like the jellyfish! **(b)** The *GFP* gene 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.

(a): © Advanced Cell Technology, Inc., Worcester, Massachusetts; (b): Photo taken by Flaminia Catteruccia, Jason Benton and Andrea Crisanti, and assembled by www.luciariccidesign.com

CONCEPT CHECK: Why is it useful to sort male mosquitoes from females?

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. Only their fur does not glow.

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. Why is this useful? Researchers can produce a population of mosquitoes and then sterilize the males. The ability to rapidly sort males and females makes it possible to 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 mate only once before they die. 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, 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. Explain how proteins are largely responsible for cell structure and function.
3. Outline how DNA stores the information to make proteins.

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 and among different species.

Genetics is centered on the study of genes. A gene is classically defined as a unit of heredity. At the molecular level, a **gene** is a segment of DNA that produces a functional product. The functional product of most genes is a polypeptide, which is a linear sequence of amino acids that folds into units that constitute proteins. In addition, 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. The 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 traits.

In this section, we examine the general features of life, beginning with the molecular level and ending with populations of organisms. As will become apparent, 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 an overview of topics they have 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 29.

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 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. RNA, proteins, and some carbohydrates are 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 building blocks called nucleotides!

The formation of cellular structures relies on the interactions of molecules and macromolecules. For example, nucleotides are connected together to make DNA, which is a constituent of chromosomes (**Figure 1.4**). In addition, DNA is associated with many proteins that provide organization to the structure of chromosomes. 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 organization of chromosomes within a cell nucleus protects the chromosomes from mechanical damage and provides a single compartment for genetic activities such as gene transcription. As a general theme, the formation of large cellular structures arises from interactions among different molecules and macromolecules. These cellular structures, in turn, 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. The entire collection of proteins that a cell makes at a given time is called its **proteome.** The range of functions among different types of proteins is truly remarkable. Some proteins help determine the shape and structure of a given

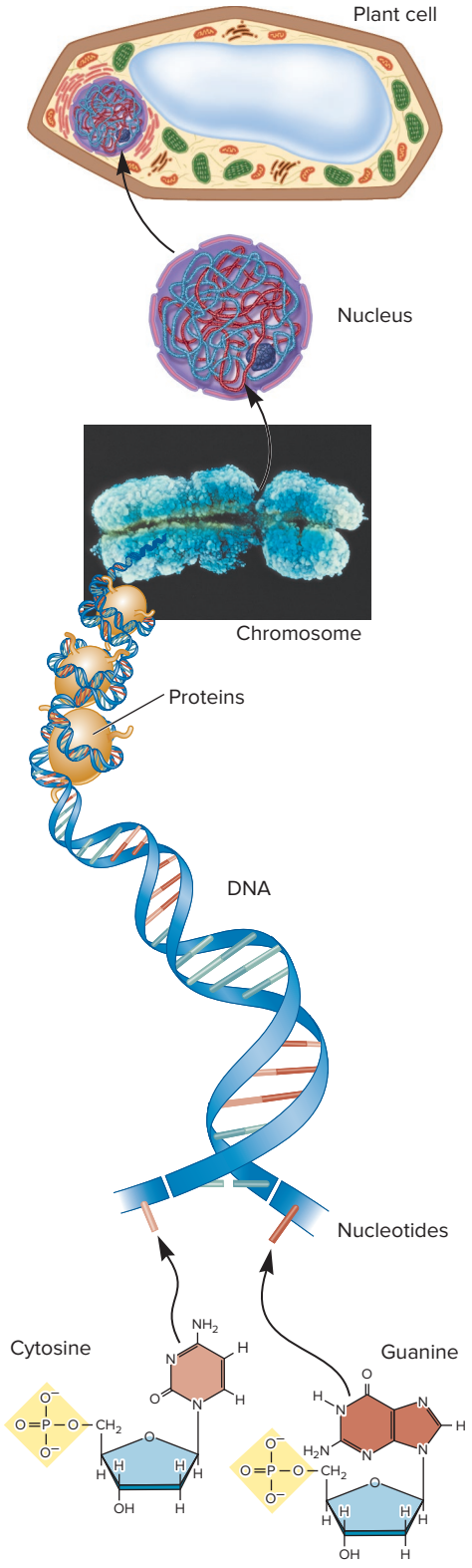


FIGURE 1.4 Molecular organization of a living cell. Cellular structures are constructed from smaller building blocks. In this example, DNA is formed from the linkage of nucleotides to produce a very long macromolecule. The DNA associates with proteins to form a chromosome. The chromosomes are located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

photo: © Biophoto Associates/Science Source

CONCEPT CHECK: Is DNA a small molecule, a macromolecule, or an organelle?

cell. For example, the protein known as tubulin assembles into large structures known as microtubules, which provide the cell with internal structure and organization. Other proteins are inserted into cell membranes and aid in the transport of ions and small molecules across the membrane. **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 are known as catabolic enzymes and are important in the utilization of energy. Alternatively, anabolic enzymes and accessory proteins function in the synthesis of molecules and macromolecules throughout the cell. The construction of a cell greatly depends on its proteins that are involved in anabolism because these are required to synthesize all cellular macromolecules.

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.

DNA Stores the Information for Protein Synthesis

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 cellular 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 is an extremely complicated task 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 for the numbers produced by complex eukaryotic species 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 nucleotide 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. 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, the DNA is found within large structures known as **chromosomes.** Figure 1.5 is a micrograph of the 46 chromosomes contained in a cell from a human male; this type of image is known as a **karyotype.** 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 contain about 1000 different protein-encoding genes.

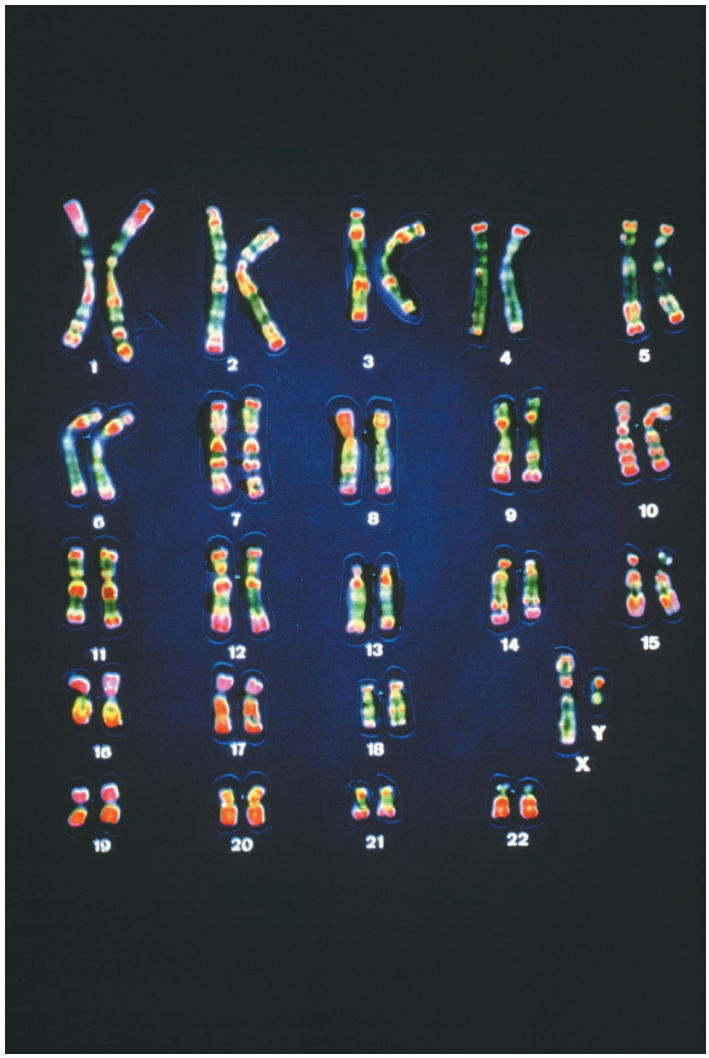


FIGURE 1.5 A micrograph of the 46 chromosomes found in a cell from a human male.

CONCEPT CHECK: Which types of macromolecules are found in chromosomes?

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 referred to as **gene expression.** At the molecular level, the information