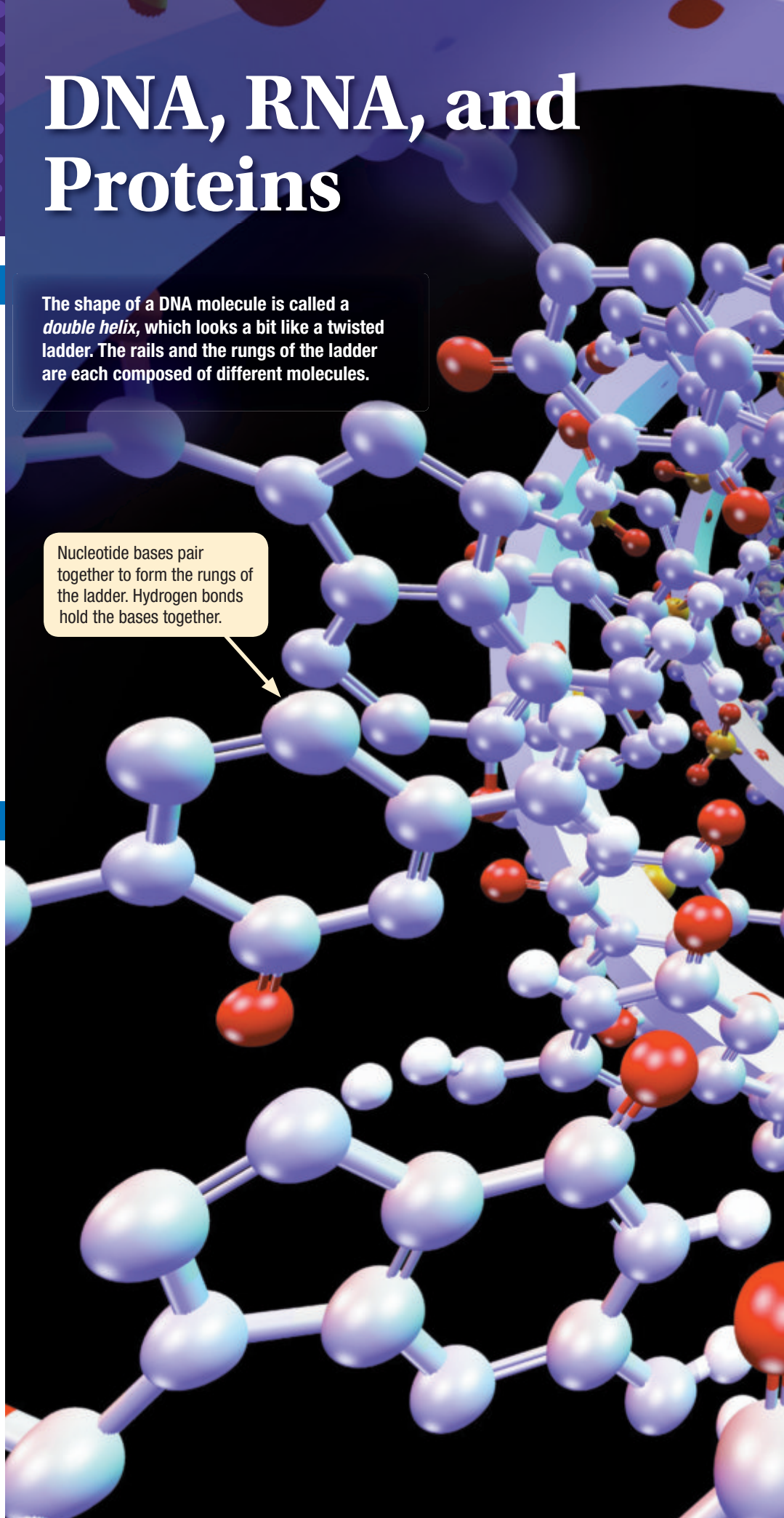
Chapter 13

DNA, RNA, and Proteins

Preview

Why It Matters

Did you know that DNA is found in the cells of all organisms? A unique set of genes makes one organism different from another, but DNA is the universal molecule found in all genes.



Section 1

The Structure of DNA

Key Ideas	Key Terms	Why It Matters
❯ What is genetic material composed of? ❯ What experiments helped identify the role of DNA? ❯ What is the shape of a DNA molecule? ❯ How is information organized in a DNA molecule? ❯ What scientific investigations led to the discovery of DNA's structure?	**gene** **DNA** **nucleotide** **purine** **pyrimidine**	DNA is the "blueprint" from which all living things are made, so understanding DNA is key to understanding life.

Unless you have an identical twin, you—like the sisters in **Figure 1**—share some, but not all, characteristics with family members.

DNA: The Genetic Material

In the 1800s, Gregor Mendel showed that traits are passed from parents to offspring. Many years later, scientists have discovered how these traits are passed on. The instructions for inherited traits are called **genes.** Before the 1950s, however, scientists did not know what genes were made of. We now know that genes are made of small segments of deoxyribonucleic acid, or **DNA.** ❯ **DNA is the primary material that causes recognizable, inheritable characteristics in related groups of organisms.**

DNA is a relatively simple molecule, composed of only four different subunits. For this reason, many early scientists did not consider DNA to be complex enough to be genetic material. A few key experiments led to the discovery that DNA is, in fact, genetic material.

❯ **Reading Check** ***What are genes composed of? (See Appendix for answers to Reading Checks.)***

gene a segment of DNA that is located in a chromosome and that codes for a specific hereditary trait

DNA deoxyribonucleic acid, the material that contains the information that determines inherited characteristics

Figure 1 These sisters share many traits but also have differences. ❯ **What role do genes play in passing traits from parents to offspring?**

Searching for the Genetic Material

Once scientists discovered DNA, they began to search for its location. By the 1900s, scientists had determined that genetic material was located in cells, but they did not know exactly where. **Three major experiments led to the conclusion that DNA is the genetic material in cells. These experiments were performed by Griffith, Avery, Hershey, and Chase.**

Griffith's Discovery of Transformation In 1928, Frederick Griffith was working with two related strains of bacteria. The S strain causes pneumonia and is covered by a capsule of polysaccharides. The R strain has no capsule and does not cause pneumonia. Mice that are infected with the S bacteria get sick and die. Griffith injected mice with heat-killed S bacteria. The bacteria were dead, but the capsule was still present. The mice lived. Griffith concluded that the S bacteria cause disease.

However, when harmless, live R bacteria were mixed with the harmless, heat-killed S bacteria and were injected into mice, the mice died. Griffith had discovered *transformation,* which is a change in genotype that is caused when cells take up foreign genetic material. Griffith's experiments, shown in **Figure 2,** led to the conclusion that genetic material could be transferred between cells. But no one knew that this material was DNA.

Avery's Experiments with Nucleic Acids In the 1940s, Oswald Avery wanted to determine whether the transforming agent in Griffith's experiments was protein, RNA, or DNA. Avery and his colleagues used enzymes to destroy each of these molecules in heat-killed S bacteria. They found that bacteria that were missing protein and RNA were able to transform R cells into S cells. However, bacteria that were missing DNA did not transform R cells. The scientists concluded that DNA is responsible for transformation in bacteria.

In 1952, Alfred Hershey and Martha Chase thought that they could support Avery's conclusions by showing how DNA and proteins cross the cell membrane. Their experiment would determine how DNA affected other cells.

READING TOOLBOX

Describing Time Use specific time markers and **Figure 2** to describe Griffith's experiment.

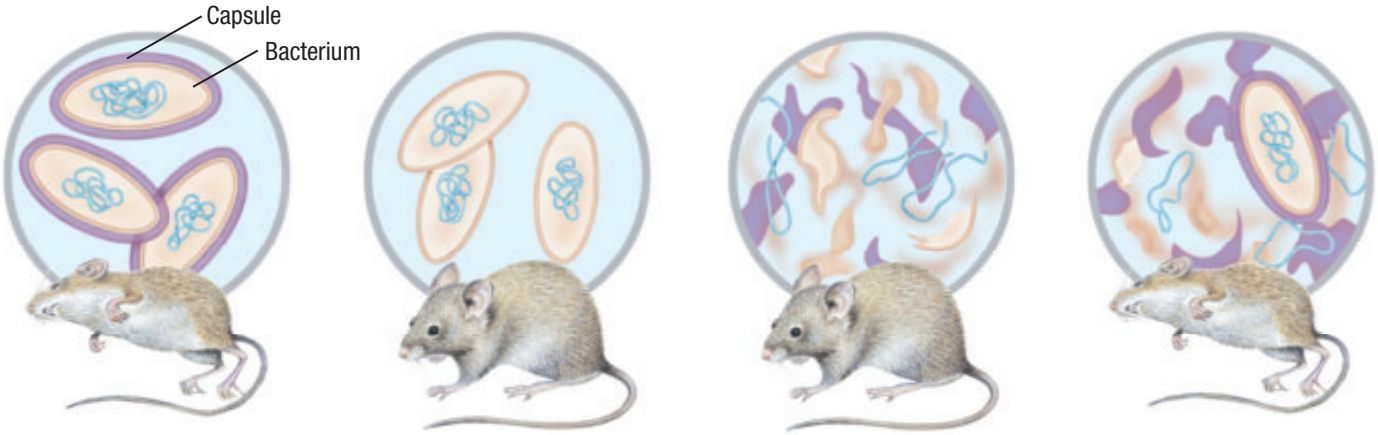


Figure 2 Griffith discovered that harmless bacteria could cause disease when they were mixed with killed disease-causing bacteria. **What were the variables in Griffith's experiments?**

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Hershey-Chase Experiment

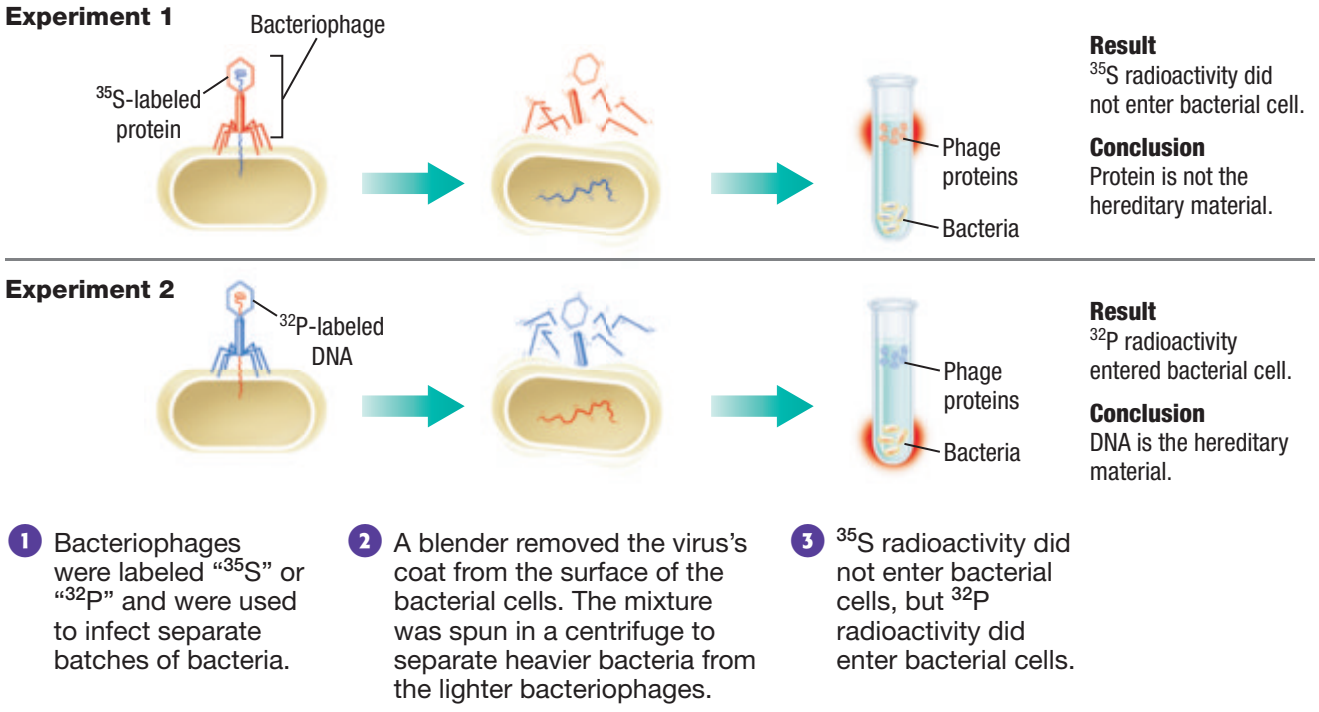

Figure 3 Bacteriophages were used to show that DNA, not protein, is the genetic material in viruses.

Hershey-Chase Experiment Hershey and Chase studied bacteriophages, viruses that infect bacterial cells and cause the cells to produce viruses. Bacteriophages are made up of proteins and DNA, but which of these two molecules is the genetic material in viruses? **Figure 3** illustrates their experiment.

Step 1 First, Hershey and Chase knew that proteins contain some sulfur but no phosphorus and that DNA contains phosphorus but no sulfur. The scientists grew two sets of viruses in environments that were enriched with different radioactive isotopes. One set of viruses had radioactive sulfur (^{35}S) atoms attached to proteins. The other set had radioactive phosphorus (^{32}P) atoms attached to DNA.

Step 2 Second, each set of viruses was allowed to infect separate batches of nonradioactive bacteria. Because radioactive elements release particles that can be detected with machines, they can be tracked in a biological process. Each of the batches was then separated into parts that contained only bacteria or only viruses.

Step 3 The infected bacteria from the ^{35}S batch did not contain radioactive sulfur, so proteins could not have infected the bacteria. However, the infected bacteria from the ^{32}P batch did contain radioactive phosphorus. DNA had infected the bacteria.

Hershey and Chase concluded that only the DNA of viruses is injected into bacterial cells. The injected DNA caused the bacteria to produce viral DNA and proteins. This finding indicated that rather than proteins, DNA is the hereditary material, at least in viruses.

The Shape of DNA

After the important experiments in the early 1950s, most scientists were convinced that genes were made of DNA, but nothing was known about DNA's structure. The research of many scientists led James Watson and Francis Crick, two young researchers at Cambridge University, to piece together a model of DNA's structure. Knowing the structure of DNA allowed scientists to understand how DNA could serve as genetic material.

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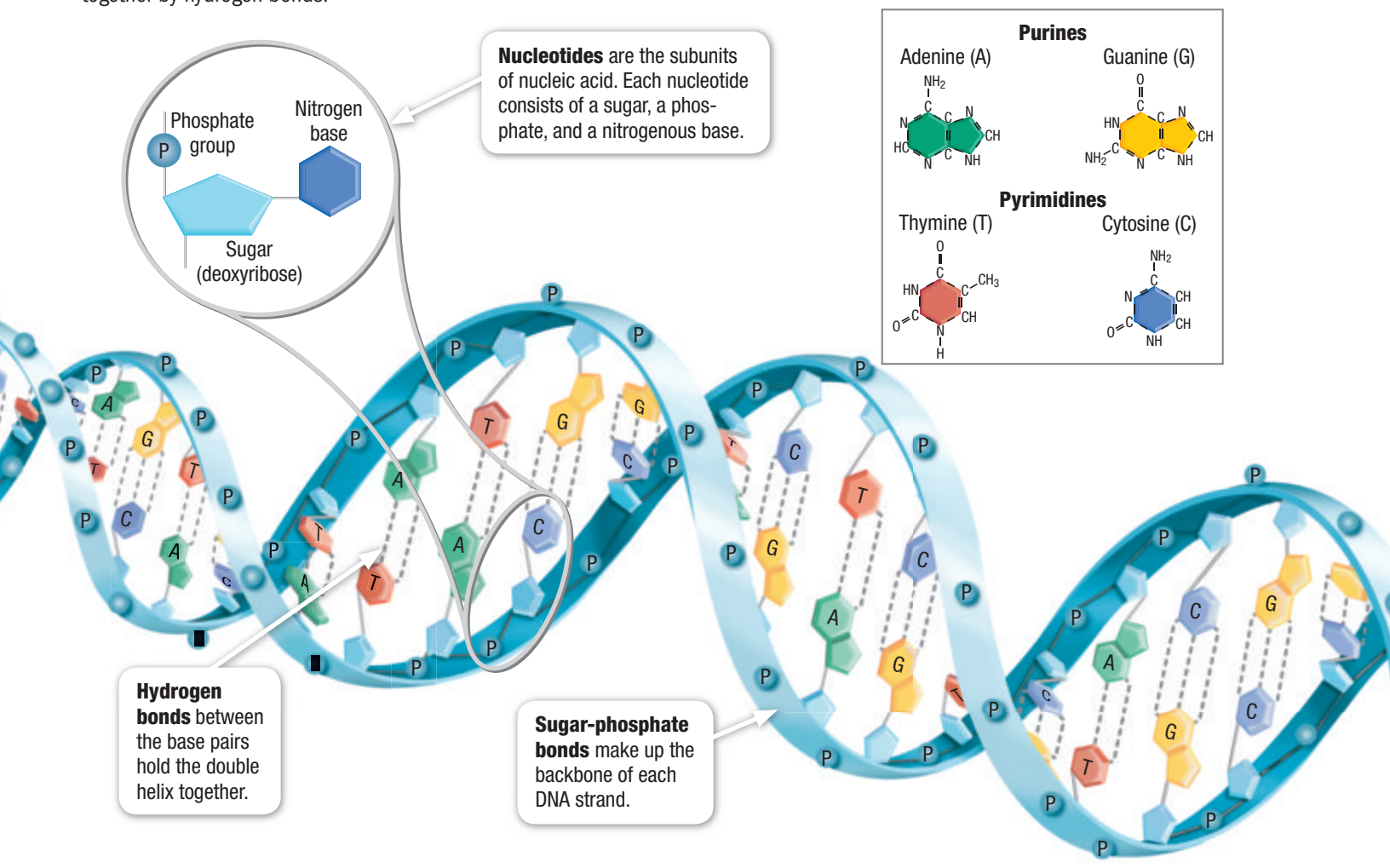
A Winding Staircase **A DNA molecule is shaped like a spiral staircase and is composed of two parallel strands of linked subunits.** This spiral shape is known as a *double helix,* as **Figure 4** shows. Each strand is made up of linked subunits called nucleotides.

Parts of the Nucleotide Subunits Each **nucleotide** is made up of three parts: a phosphate group, a five-carbon sugar molecule, and a nitrogen-containing base. **Figure 4** shows how these three parts are arranged to form a nucleotide. The phosphate groups and the sugar molecules of nucleotides link together to form a "backbone" for a DNA strand. The five-carbon sugar in DNA is called *deoxyribose*, from which DNA gets its full name, *deoxyribonucleic acid.* The bases of nucleotides pair together to connect the two strands.

Figure 4 Watson and Crick's model of DNA is a double helix that is composed of two nucleotide chains. The chains are twisted around a central axis and are held together by hydrogen bonds.



Hands-On

QuickLab

15 min

DNA's Structure

Build a model to help you understand the structure of DNA.

Procedure

1. Use the following materials to build a model of DNA: **plastic straws** cut into 3 cm sections, a **metric ruler, scissors, pushpins (four different colors),** and **paper clips.** Your model should have at least 12 nucleotides on each strand.
2. As you design your model, decide how to use the straws, pushpins, and paper clips to represent the three components of a nucleotide and how to link the nucleotides together.

Analysis

1. **Describe** your model by using words or drawings. Are the two strands in your model identical? Explain why or why not.
2. **Explain** how you determined which nucleotides were placed on each strand of DNA in your model.
3. CRITICAL THINKING **Inferring Relationships** How might the structure of DNA be beneficial when a cell copies its DNA before cell division?

The Information in DNA

The structure of DNA is very important in the transfer of genetic information. **The information in DNA is contained in the order of the bases, while the base-pairing structure allows the information to be copied.**

nucleotide (NOO klee oh TIED) in a nucleic acid chain, a subunit that consists of a sugar, a phosphate, and a nitrogenous base

purine (PYOOR EEN) a nitrogenous base that has a double-ring structure; adenine or guanine

pyrimidine (pi RIM uh DEEN) a nitrogenous base that has a single-ring structure; in DNA, either thymine or cytosine

Nitrogenous Bases In DNA, each nucleotide has the same sugar molecule and phosphate group, but the nucleotide can have one of four nitrogenous bases. The four kinds of bases, shown in **Figure 4,** are *adenine* (A), *guanine* (G), *thymine* (T), and *cytosine* (C). Bases A and G are classified as **purines.** Purines have two rings of carbon and nitrogen atoms per base. Bases T and C are **pyrimidines.** Pyrimidines have one ring of carbon and nitrogen atoms per base.

Base-Pairing Rules A purine on one strand of a DNA molecule is always paired with a pyrimidine on the other strand. More specifically, adenine always pairs with thymine, and guanine always pairs with cytosine. These *base-pairing rules* are dictated by the chemical structure of the bases. The structure and size of the nitrogenous bases allow for only these two pair combinations. The base pairs are held together by weak hydrogen bonds. Adenine forms two hydrogen bonds with thymine, while cytosine forms three hydrogen bonds with guanine. The hydrogen bonds are represented by dashed lines in **Figure 4.** The hydrogen bonds between bases keep the two strands of DNA together.

Reading Check *How are base-pairs held together?*

ACADEMIC VOCABULARY

complementary being separate parts that improve or enhance each other

Complementary Sides **Figure 5** shows a simpler way to represent base-pairing. Paired bases are said to be complementary because they fit together like puzzle pieces. For example, if the sequence of nitrogen bases on one strand is TATGAGAGT, the sequence of nitrogen bases on the other strand must be ATACTCTCA. The pairing structure ensures that each strand of a DNA molecule contains the same information. However, the information on one strand is in reverse order from that on the other strand.

Discovering DNA's Structure

How were James Watson and Francis Crick able to determine the double-helical structure of DNA? ❯ **Watson and Crick used information from experiments by Chargaff, Wilkins, and Franklin to determine the three-dimensional structure of DNA.**

Observing Patterns: Chargaff's Observations In 1949, biochemist Erwin Chargaff made an interesting observation about DNA. His data showed that for each organism that he studied, the amount of adenine always equaled the amount of thymine (A = T). Similarly, the amount of guanine always equaled the amount of cytosine (G = C). **Figure 6** shows some of Chargaff's data. Watson and Crick used this information to determine how nucleotides are paired in DNA.

Using Technology: Photographs of DNA The significance of Chargaff's data became clear when scientists began using X rays to study the structures of molecules. In 1952, Rosalind Franklin, shown in **Figure 6,** and Maurice Wilkins developed high-quality X-ray diffraction images of strands of DNA. These photographs suggested that the DNA molecule resembled a tightly coiled helix and was composed of two or three chains of nucleotides.

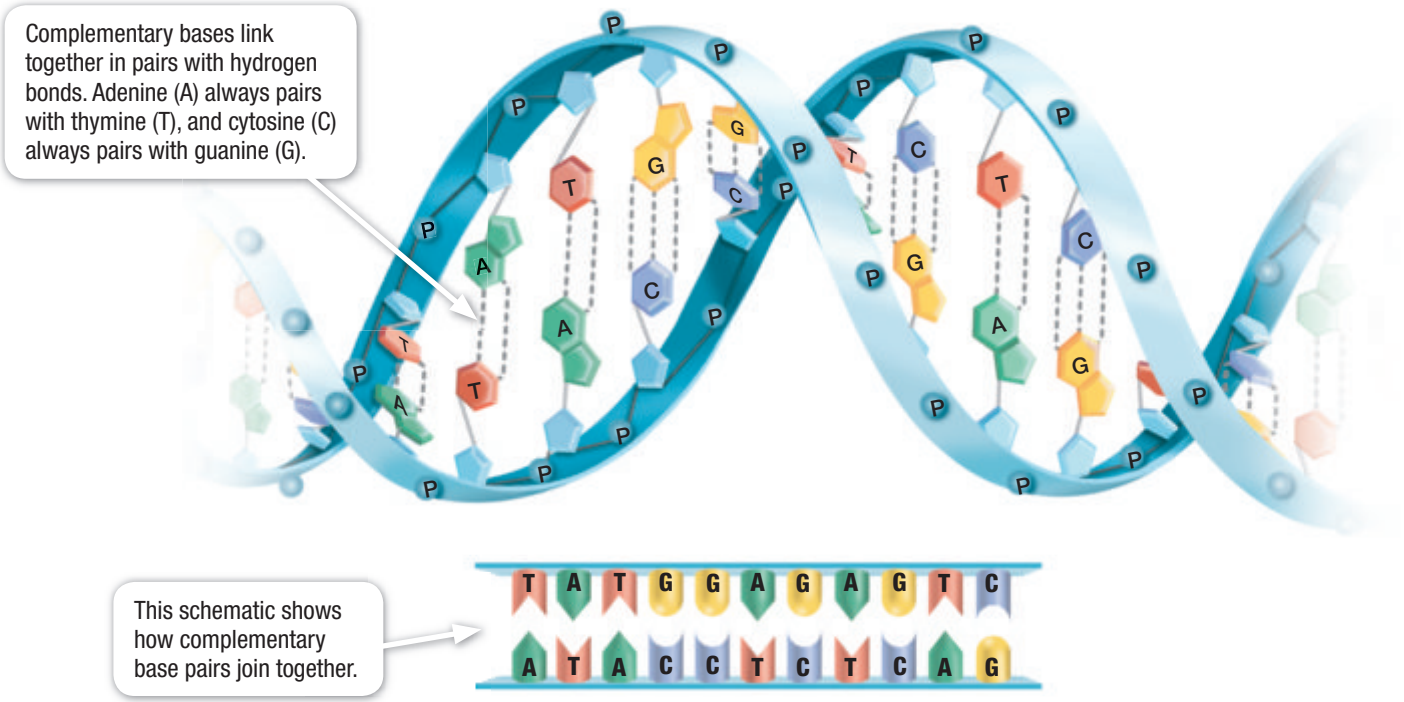
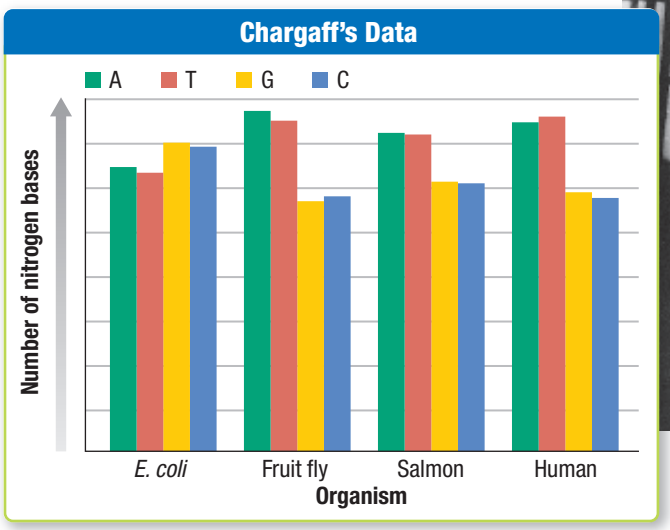


Figure 5 The diagram of DNA below the double helix simplifies the base pairing that occurs between DNA strands.



Watson & Crick

Franklin

Figure 6 Chargaff's data and Franklin's X-ray diffraction studies were instrumental in the discovery of DNA's structure. Watson and Crick are shown with their tin and wire model of DNA.

Watson and Crick's Model of DNA To determine the three-dimensional structure of DNA, Watson and Crick set out to build a model of DNA. They knew that any model would have to take into account both Chargaff's data and the findings from Franklin's X-ray diffraction studies. In 1953, Watson and Crick used these findings, along with knowledge of chemical bonding, to create a complete three-dimensional model of DNA. By using paper models of the bases, Watson and Crick worked out the pairing structure of purines with pyrimidines. Then, they built a large model of a DNA double helix by using tin, wire, and other materials. Their model showed a "spiral staircase" in which two strands of nucleotides twisted around a central axis. **Figure 6** shows Watson and Crick with their model.

Nine years later, in 1962, the Nobel Prize was awarded to Watson, Crick, and Wilkins for their discovery. Rosalind Franklin died in 1958 and was not named in the award.

Reading Check ***How was X-ray diffraction used to model the structure of DNA?***

Section 1 **Review**

KEY IDEAS

1. **Identify** the substance that makes up genetic material.
2. **Name** the experiments that identified the role of DNA.
3. **Draw** the shape of a DNA molecule.
4. **Relate** the structure of DNA to the function of DNA as a carrier of information.
5. **Name** the studies that led to the discovery of DNA's structure.

CRITICAL THINKING

6. **Applying Information** If a DNA strand has the nucleotide sequence of CCGAGATTG, what is the nucleotide sequence of the complementary strand?
7. **Applying Information** What might Hershey and Chase have concluded if they had found ^{35}S instead of ^{32}P in bacterial cells? Explain your answer.

USING SCIENCE GRAPHICS

8. **Evaluating Graphics** Look at the graph of Chargaff's data in **Figure 6.** How do the amounts of adenine compare with the amounts of thymine across species? How do the amounts of cytosine and guanine compare? How did these data lead to the discovery of the base-pairing rules by Chargaff? How was this discovery used to determine DNA's structure?

Section 2

Replication of DNA

Key Ideas	Key Terms	Why It Matters
How does DNA replicate, or make a copy of itself? What are the roles of proteins in DNA replication? How is DNA replication different in prokaryotes and eukaryotes?	DNA replication DNA helicase DNA polymerase	Understanding how DNA is copied has led to a better understanding of genetic diseases and cancer.

When cells divide, each new cell contains an exact copy of the original cell's DNA. How is this possible?

DNA Replication

Remember that DNA is made of two strands of complementary base pairs. Adenine always pairs with thymine, and guanine always pairs with cytosine. If the strands of DNA are separated, as shown in **Figure 7,** each strand can serve as a pattern to make a new complementary strand. This separation allows two exact copies of DNA to be made from the original DNA molecule. Copying the DNA before cell division allows each new cell to have DNA identical to the original cell's.

The process of making a copy of DNA is called **DNA replication.** **In DNA replication, the DNA molecule unwinds, and the two sides split. Then, new bases are added to each side until two identical sequences result.** DNA replication occurs before a cell divides so that each cell has a complete copy of DNA. The basic steps of DNA replication are described below and are illustrated in **Figure 8** on the next page.

Step 1 Unwinding and Separating DNA Strands Before DNA replication can begin, the double helix unwinds. The two complementary strands of DNA separate from each other and form Y shapes. These Y-shaped areas are called *replication forks.* **Figure 7** shows two replication forks in a molecule of DNA.

Step 2 Adding Complementary Bases At the replication fork, new nucleotides are added to each side and new base pairs are formed according to the base-pairing rules. For example, if one of the original strands has thymine, then adenine will be paired with thymine as the new strand forms. Thus, the original two strands serve as a template for two new strands. As more nucleotides are added, two new double helixes begin to form. The process continues until the whole DNA sequence has been copied.

Step 3 Formation of Two Identical DNA Molecules This process of DNA replication produces two identical DNA molecules. Each double-stranded DNA helix is made of one new strand of DNA and one original strand of DNA. The nucleotide sequences in both of these DNA molecules are identical to each other and to the original DNA molecule.

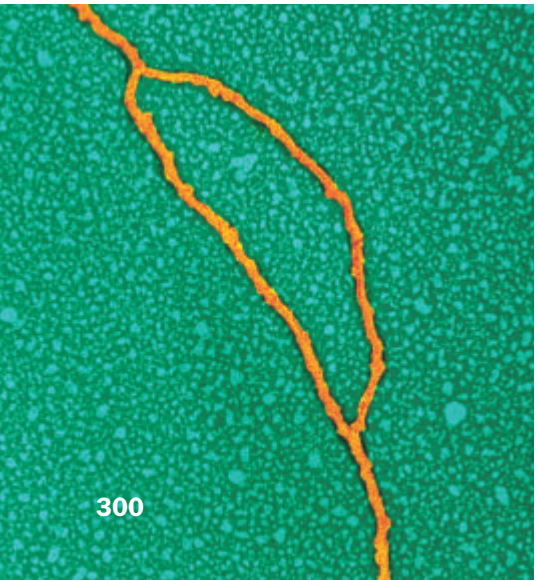


Figure 7 When the two strands of the DNA helix separate, Y-shaped replication forks form.

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DNA Replication

1 Proteins called *helicases* separate the two original DNA strands.

2 Complementary nucleotides are added to each strand by DNA polymerases.

3 Two DNA molecules are formed that are identical to the original DNA molecule.

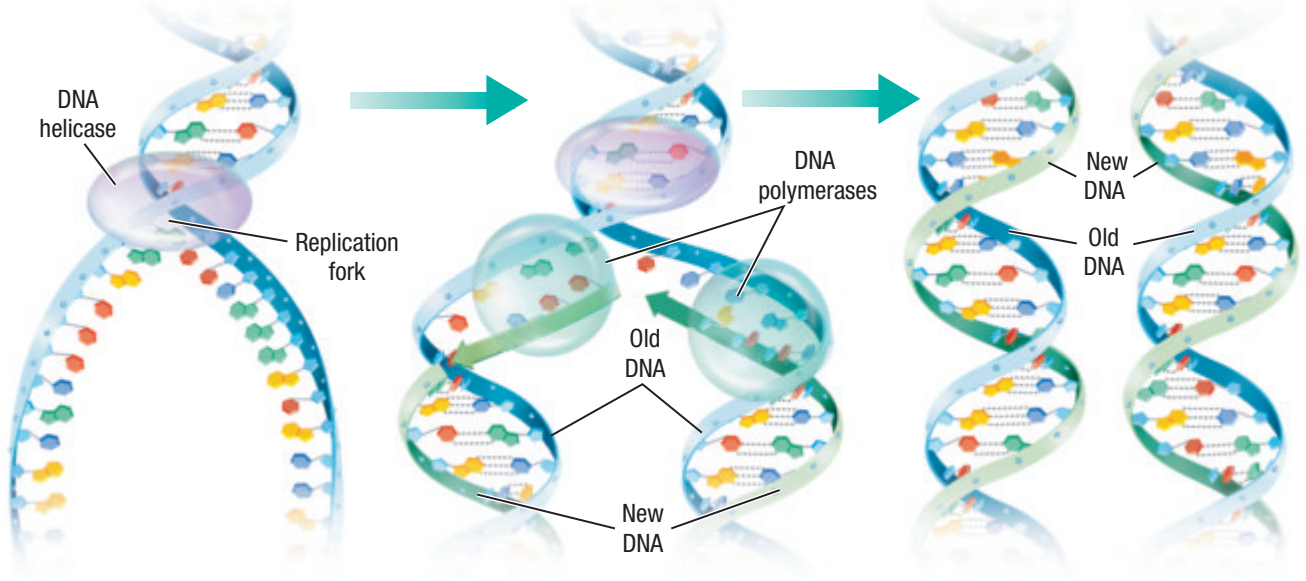


Figure 8 DNA replication results in two identical DNA strands.

Replication Proteins

During the replication of DNA, many proteins form a machinelike complex of moving parts. Each protein has a specific function.

DNA Helicase Proteins called **DNA helicases** unwind the DNA double helix during DNA replication. These proteins wedge themselves between the two strands of the double helix and break the hydrogen bonds between the base pairs. This process causes the helix to unwind and forms a replication fork, as **Figures 7** and **8** show. Additional proteins keep the two strands separated so that replication can occur.

DNA Polymerase Proteins called **DNA polymerases** catalyze the formation of the DNA molecule. At the replication fork, DNA polymerases move along each strand. The polymerases add nucleotides that pair with each base to form two new double helixes. After all of the DNA has been copied, the polymerases are released.

DNA polymerases also have a "proofreading" function. During DNA replication, errors sometimes occur, and the wrong nucleotide is added to the new strand. DNA polymerases cannot add another nucleotide unless the previous nucleotide is correctly paired with its complementary base. If a mismatch occurs, the DNA polymerase can backtrack, remove the incorrect nucleotide, and replace it with the correct one. Proofreading reduces the replication errors to about one per 1 billion nucleotides.

Reading Check ***Why is proofreading critical during replication?***

DNA replication the process of making a copy of DNA

DNA helicase (HEEL uh KAYS) an enzyme that unwinds the DNA double helix during DNA replication

DNA polymerase (puh LIM uhr AYS) an enzyme that catalyzes the formation of the DNA molecule

READING TOOLBOX

Word Parts In your own words, write a definition of *helicase* and *polymerase,* the names of the enzymes involved in DNA replication, based on the meanings of each term's word parts.

Prokaryotic and Eukaryotic Replication

Both prokaryotes and eukaryotes replicate their DNA to reproduce and grow. Recall that the packaged DNA in a cell is called a *chromosome*. All cells have chromosomes, but eukaryotes and prokaryotes replicate their chromosomes differently. **› In prokaryotic cells, replication starts at a single site. In eukaryotic cells, replication starts at many sites along the chromosome.**

Prokaryotic DNA Replication Prokaryotic cells usually have a single DNA molecule, or chromosome. Prokaryotic chromosomes are a closed loop, may contain protein, and are attached to the inner cell membrane. Replication begins at one place along the DNA loop. Two replication forks begin at that single point, which is known as the origin of replication. Replication occurs in opposite directions until the replication forks meet on the opposite side of the DNA loop and the entire molecule has been copied. **Figure 9** shows prokaryotic DNA replication.

Eukaryotic DNA Replication While prokaryotes have a single chromosome, eukaryotic cells often have several chromosomes. Eukaryotic chromosomes differ from the simple, looped chromosomes found in prokaryotic cells. Eukaryotic chromosomes are linear, and they contain both DNA and protein. Recall that the long molecules of DNA are tightly wound around proteins called *histones* and are packaged into thick chromosome fibers.

By starting replication at many sites along the chromosome, eukaryotic cells can replicate their DNA faster than prokaryotes can. As in prokaryotic replication, two distinct replication forks form at each start site, and replication occurs in opposite directions. This process forms replication "bubbles" along the DNA molecule. The replication bubbles continue to get larger as more of the DNA is copied. As **Figure 9** shows, they eventually meet to form two identical, linear DNA molecules. Because multiple replication forks are working at the same time, an entire human chromosome can be replicated in about eight hours. Then, the cell will be ready to divide.

ACADEMIC VOCABULARY

distinct separate; not the same

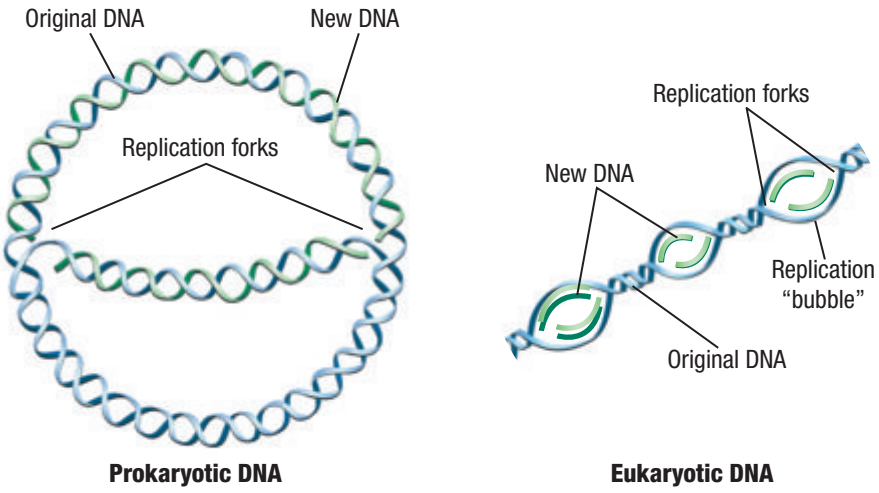


Figure 9 Prokaryotic and eukaryotic DNA have different numbers of replication forks. **› Why does replication in eukaryotes involve more replication forks?**

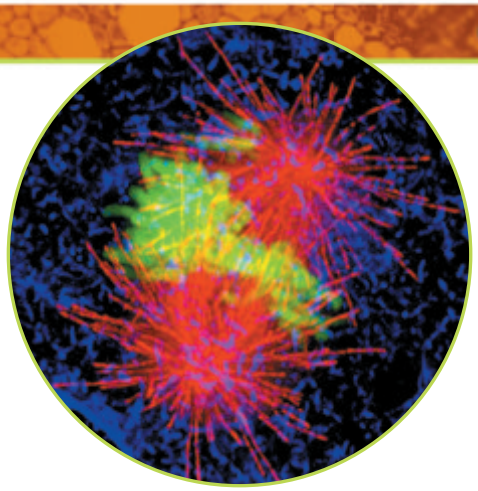
Data

QuickLab

15 min

DNA Replication Rate

Cancer is a disease caused by cells that divide uncontrollably. Scientists studying drugs that prevent cancer often measure the effectiveness of a drug by its effect on DNA replication. During normal DNA replication, nucleotides are added at a rate of about 50 nucleotides per second in mammals and 500 nucleotides per second in bacteria.



Analysis

1. **Calculate** the time it would take a bacterium to add 4,000 nucleotides to one DNA strand undergoing replication.
2. **Calculate** the time it would take a mammalian cell to add 4,000 nucleotides to one DNA strand undergoing replication.
3. CRITICAL THINKING **Predicting Outcomes** How would the total time needed to add the 4,000 nucleotides be affected if a drug that inhibits DNA polymerases were present? Explain your answer.

Size of Eukaryotic DNA The smallest eukaryotic chromosomes are often 10 times the size of a prokaryotic chromosome. If a scientist took all of the DNA in a single human cell and laid the DNA in one line (that is, laid the DNA from all 46 chromosomes end to end), the line would be 2 m long. In contrast, if the scientist laid out the DNA from one bacterial chromosome, the line would be only about 0.25 cm long. In fact, the length of eukaryotic chromosomes is so long that replication of a typical human chromosome would take 33 days if there were only one origin of replication.

Each human chromosome is replicated in about 100 sections that are 100,000 nucleotides long, each section with its own starting point. With multiple replication forks working in concert, an entire human chromosome can be replicated in about 8 hours.

› **Reading Check** *How is a "replication bubble" formed?*

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Section 2 Review

KEY IDEAS

1. **Describe** the steps of DNA replication.
2. **Compare** the roles of DNA helicases and DNA polymerases.
3. **Compare** the process of DNA replication in prokaryotes and in eukaryotes.

CRITICAL THINKING

4. **Inferring Relationships** What is the relationship between DNA polymerases and mutations in DNA?
5. **Relating Concepts** Cancer is a disease caused by cells that divide uncontrollably. Scientists are researching drugs that inhibit DNA polymerase as potential anti-cancer drugs. Why would these drugs be useful against cancer?

ALTERNATIVE ASSESSMENT

6. **Replication Model** Conduct research on the shapes of prokaryotic and eukaryotic chromosomes. Draw a model of each type of chromosome. How does the structure of chromosomes in prokaryotic cells and eukaryotic cells affect the DNA replication processes in a cell?

Section 3

RNA and Gene Expression

Key Ideas	Key Terms	Why It Matters
What is the process of gene expression? What role does RNA play in gene expression? What happens during transcription? How do codons determine the sequence of amino acids that results after translation? What are the major steps of translation? Do traits result from the expression of a single gene?	RNA gene expression transcription translation codon	Traits, such as eye color, are determined by proteins that are built according to instructions coded in DNA.

Proteins perform most of the functions of cells. DNA provides the original "recipe," or information, from which proteins are made in the cell. However, DNA does not directly make proteins. A second type of nucleic acid, ribonucleic acid, or **RNA,** is essential in taking the genetic information from DNA and building proteins.

An Overview of Gene Expression

Gene expression is the manifestation of genes into specific traits.

Gene expression produces proteins by transcription and translation. This process takes place in two stages, both of which involve RNA. **Figure 10** illustrates the parts of the cell that play a role in gene expression.

Transcription: DNA to RNA The first stage of gene expression, which is making RNA from the information in DNA, is called **transcription.** You can think of transcription as copying (transcribing) notes from the board (DNA) to a notebook (RNA).

RNA ribonucleic acid, a natural polymer that is present in all living cells and that plays a role in protein synthesis

gene expression the manifestation of the genetic material of an organism in the form of specific traits

transcription the process of forming a nucleic acid by using another molecule as a template

translation the portion of protein synthesis that takes place at ribosomes and that uses the codons in mRNA molecules to specify the sequence of amino acids in polypeptide chains

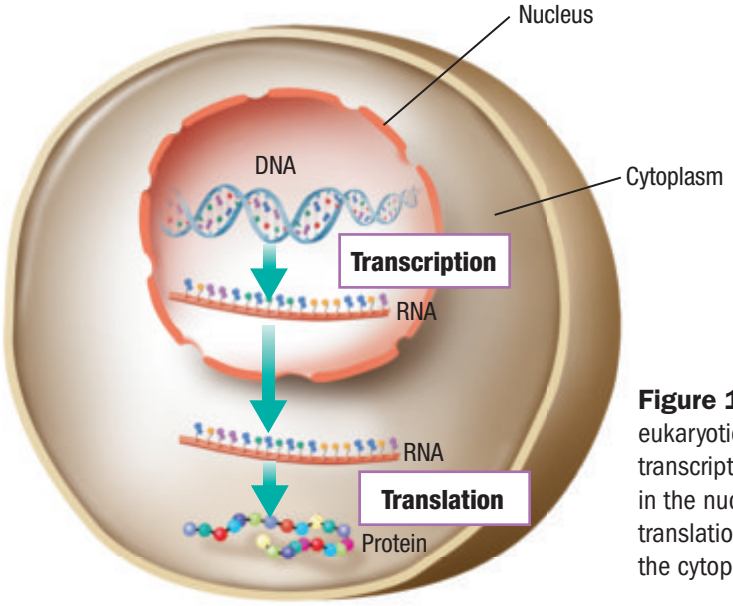

Figure 10 In eukaryotic cells, gene transcription occurs in the nucleus and translation occurs in the cytoplasm.

Translation: RNA to Proteins The second stage of gene expression, called **translation,** uses the information in RNA to make a specific protein. Translation is similar to translating a sentence in one language (RNA, the nucleic acid "language") to another language (protein, the amino acid "language").

RNA: A Major Player

All of the steps in gene expression involve RNA. Several types of RNA are used in transcription and translation. **› In cells, three types of RNA complement DNA and translate the genetic code into proteins.** But what exactly is RNA, and how does it compare to DNA?

RNA Versus DNA Like DNA, RNA is a nucleic acid—a molecule made of nucleotide subunits linked together. Like DNA, RNA has four bases and carries information in the same way that DNA does.

RNA differs from DNA in three ways. First, RNA usually is composed of one strand of nucleotides rather than two strands. The structural difference between the two nucleotides is shown in **Figure 11.** Second, RNA nucleotides contain the five-carbon sugar *ribose* rather than the sugar deoxyribose. Ribose contains one more oxygen atom than deoxyribose does. And third, RNA nucleotides have a nitrogenous base called *uracil* (U) instead of the base thymine (T). Although no thymine (T) bases are found in RNA, the other bases (A, G, and C) are identical to the bases found in DNA. In place of thymine, uracil (U) is complementary to adenine (A) whenever RNA pairs with another nucleic acid.

Types of RNA There are several types of RNA. Three main types of RNA play a role in gene expression. These types are messenger RNA, transfer RNA, and ribosomal RNA.

Messenger RNA When DNA is transcribed into RNA, *messenger RNA* (mRNA) is the type of RNA that is produced. mRNA is complementary to the DNA sequence of a gene. The mRNA carries instructions for making a protein from a gene and delivers them to the site of translation.

Transfer RNA During translation, *transfer RNA* (tRNA) "reads" the mRNA sequence. Then, tRNA translates the mRNA sequence into a specific sequence of protein subunits, or amino acids. tRNA molecules have amino acids attached to them, and the tRNA molecules act as decoders by matching the mRNA sequence and placing the amino acids on growing protein chains.

Ribosomal RNA Protein production occurs on cellular structures called *ribosomes*. Ribosomes are made up of about 80 protein molecules (ribosomal proteins) and several large RNA molecules. The RNA that is found in ribosomes is called *ribosomal RNA* (rRNA). A cell's cytoplasm contains thousands of ribosomes. In eukaryotic cells, ribosomes are attached to the endoplasmic reticulum (ER), which transports proteins as the proteins are produced.

› Reading Check ***What are the structural differences between RNA and DNA?***

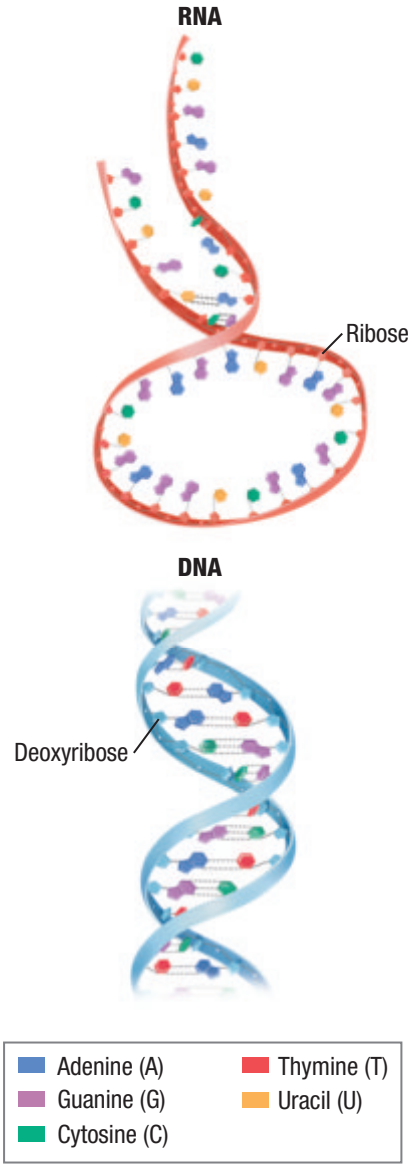

Figure 11 Both RNA (top) and DNA (bottom) are nucleic acids.

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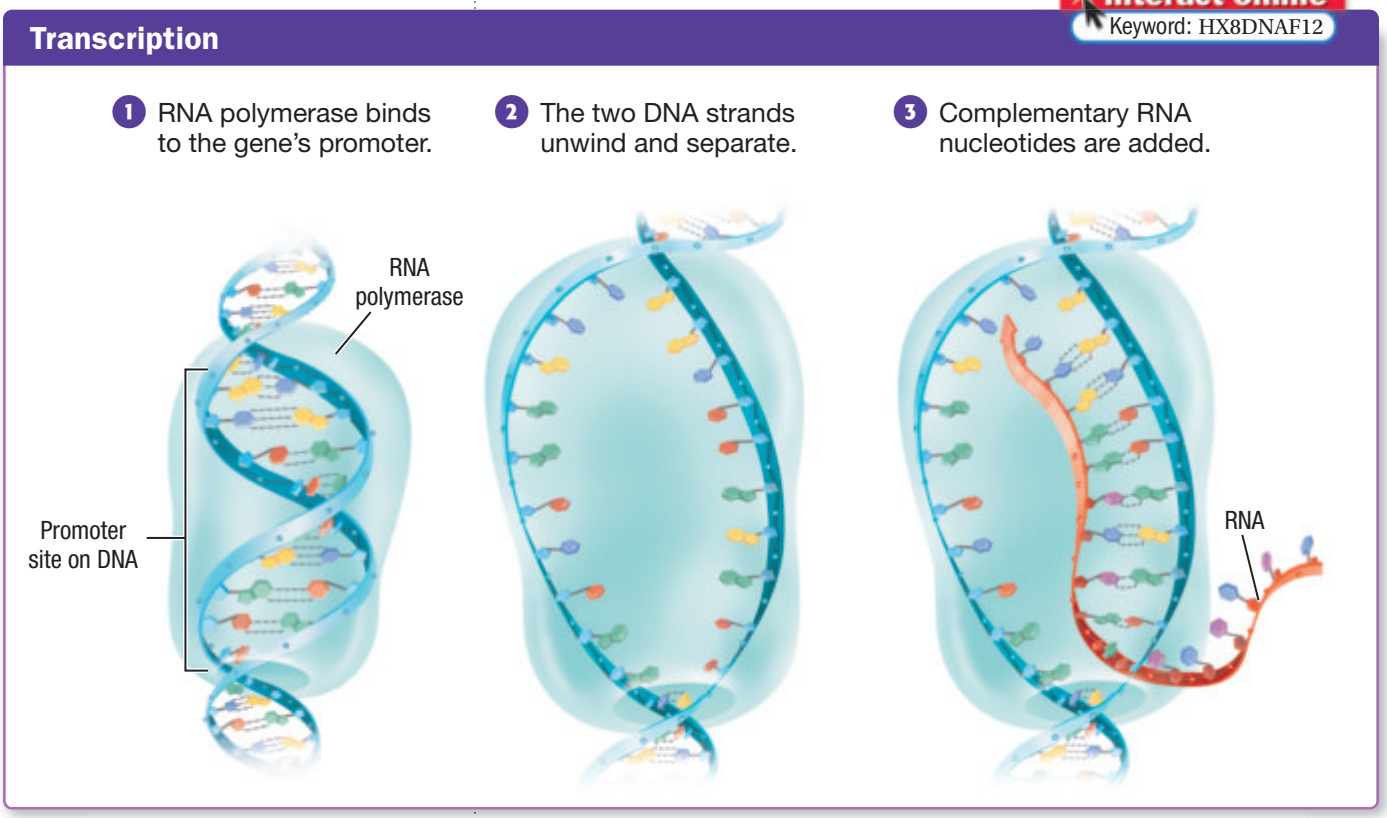

Figure 12 Transcription is the process in which mRNA is made to complement the DNA of a gene.

READING TOOLBOX

Three-Panel Flip Chart Make a three-panel flip chart to help you compare the roles of the three types of RNA used in gene expression.

Transcription: Reading the Gene

› **During transcription, the information in a specific region of DNA (a gene) is transcribed, or copied, into mRNA.** Transcription is carried out by a protein called *RNA polymerase*. The steps of transcription are described below and are shown in **Figure 12.**

Step 1 Transcription begins when RNA polymerase binds to the specific DNA sequence in the gene that is called the *promoter*. The promoter is the "start" location.

Step 2 RNA polymerase then unwinds and separates the two strands of the double helix to expose the DNA bases on each strand.

Step 3 RNA polymerase adds and links complementary RNA bases as it "reads" the gene. RNA polymerase moves along the bases on the DNA strand in much the same way that a train moves along a track. Transcription follows the base-pairing rules for DNA replication except that in RNA, uracil—rather than thymine—pairs with adenine. As RNA polymerase moves down the DNA strand, a single strand of mRNA grows. Behind the moving RNA polymerase, the two strands of DNA close up and re-form the double helix.

The RNA polymerase eventually reaches a "stop" location in the DNA. This stop signal is a sequence of bases that marks the end of each gene in eukaryotes or the end of a set of genes in prokaryotes. The result is a single strand of mRNA.

› **Reading Check** ***What is the role of a promoter?***

Transcription Versus Replication Like DNA replication, transcription uses DNA as a template for making a new molecule. In transcription, a new molecule of RNA is made from the DNA. However, in DNA replication, a new molecule of DNA is made from the DNA. Also, in DNA replication, both strands of DNA serve as templates. In contrast, during transcription only part of one of the two strands of DNA (a gene) serves as a template for the new RNA.

The Genetic Code: Three-Letter "Words"

A gene can be thought of as a "sentence" of "words" that is first transcribed and then translated into a functional protein. Once a section of a gene is transcribed into mRNA, the words can be carried from the nucleus to ribosomes in the cytoplasm. There, the words are translated to make proteins.

Codons of mRNA Each of the words in mRNA is made up of three adjacent nucleotide bases. Each three-nucleotide sequence is called a **codon.** Each codon is matched to 1 of 20 amino acids or acts as a start or stop signal for the translation stage. **Figure 13** shows this matching system for each of the possible 64 mRNA codons. For example, the codon GCU specifies the amino acid alanine. Notice that each codon specifies only one amino acid but that several amino acids have more than one codon. This system of matching codons and amino acids is called the *genetic code.* **› The genetic code is based on codons that each represent a specific amino acid.**

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codon in DNA and mRNA, a three-nucleotide sequence that encodes an amino acid or signifies a start signal or a stop signal

Figure 13 The amino acid coded for by a specific mRNA codon can be determined by following the three steps below. **› What amino acid does the codon GAA code for?**

1 Find the first base of the mRNA codon in this column of the table.

2 Follow that row to the column that matches the second base of the codon.

3 Move up or down in that box until you match the third base of the codon with this column of the chart.

Codons in mRNA

First base	Second base: U	Second base: C	Second base: A	Second base: G	Third base
U	UUU, UUC Phenylalanine UUA, UUG Leucine	UCU, UCC, UCA, UCG Serine	UAU, UAC Tyrosine UAA, UAG Stop	UGU, UGC Cysteine UGA–Stop UGG–Tryptophan	U C A G
C	CUU, CUC, CUA, CUG Leucine	CCU, CCC, CCA, CCG Proline	CAU, CAC Histidine CAA, CAG Glutamine	CGU, CGC, CGA, CGG Arginine	U C A G
A	AUU, AUC, AUA Isoleucine AUG–Start	ACU, ACC, ACA, ACG Threonine	AAU, AAC Asparagine AAA, AAG Lysine	AGU, AGC Serine AGA, AGG Arginine	U C A G
G	GUU, GUC, GUA, GUG Valine	GCU, GCC, GCA, GCG Alanine	GAU, GAC Aspartic acid GAA, GAG Glutamic acid	GGU, GGC, GGA, GGG Glycine	U C A G

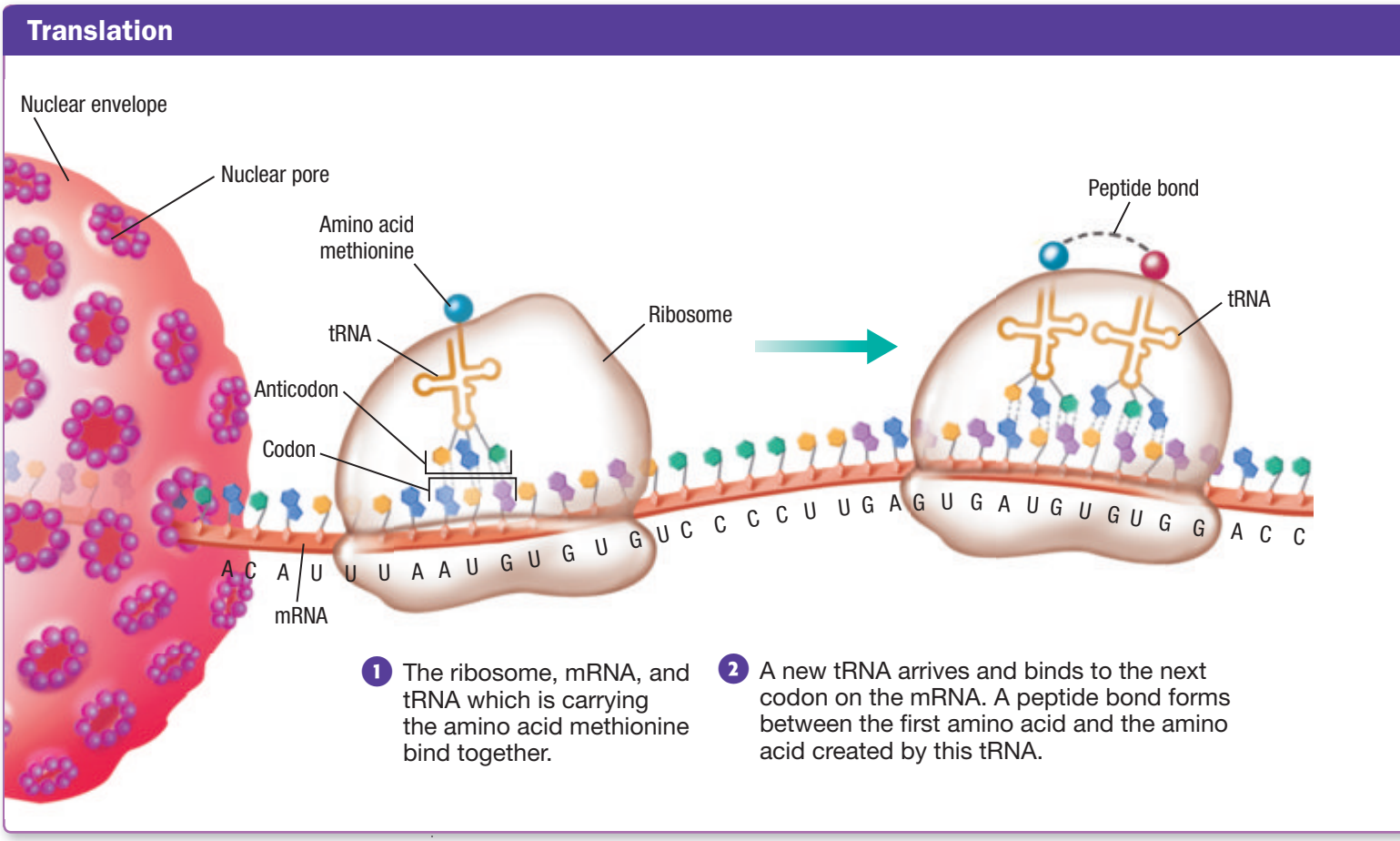

Figure 14 During translation, amino acids are assembled from information encoded in mRNA. As the mRNA codons move through the ribosome, tRNAs add specific amino acids to the growing polypeptide chain. This process continues until a stop codon is reached and the newly made protein is released.

Translation: RNA to Proteins

Translation is the process of converting the "language" of RNA (nucleotide sequences) into the "language" of proteins (amino acid sequences). **Translation occurs in a sequence of steps, involves three kinds of RNA, and results in a complete *polypeptide*.** In the cytoplasm, ribosomes are formed as tRNA, rRNA, and mRNA interact to assemble amino acid sequences that are based on the genetic code. The process of translation is summarized below and in **Figure 14.**

Step 1 Each tRNA is folded into a compact shape, as **Figure 15** shows. An amino acid is added to one end of each tRNA. The other end of the tRNA has an anticodon. An *anticodon* is a three-nucleotide sequence that is complementary to an mRNA codon. Each tRNA molecule carries the amino acid that corresponds with the tRNA's anticodon. After leaving the nucleus, the mRNA joins with a ribosome and tRNA. The mRNA start codon, AUG, signals the beginning of a protein chain. A tRNA molecule carrying methionine at one end and the anticodon, UAC, at the other end binds to the start codon.

Step 2 A tRNA molecule that has the correct anticodon and amino acid binds to the second codon on the mRNA. A peptide bond forms between the two amino acids, and the first tRNA is released from the ribosome. The tRNA leaves its amino acid behind.

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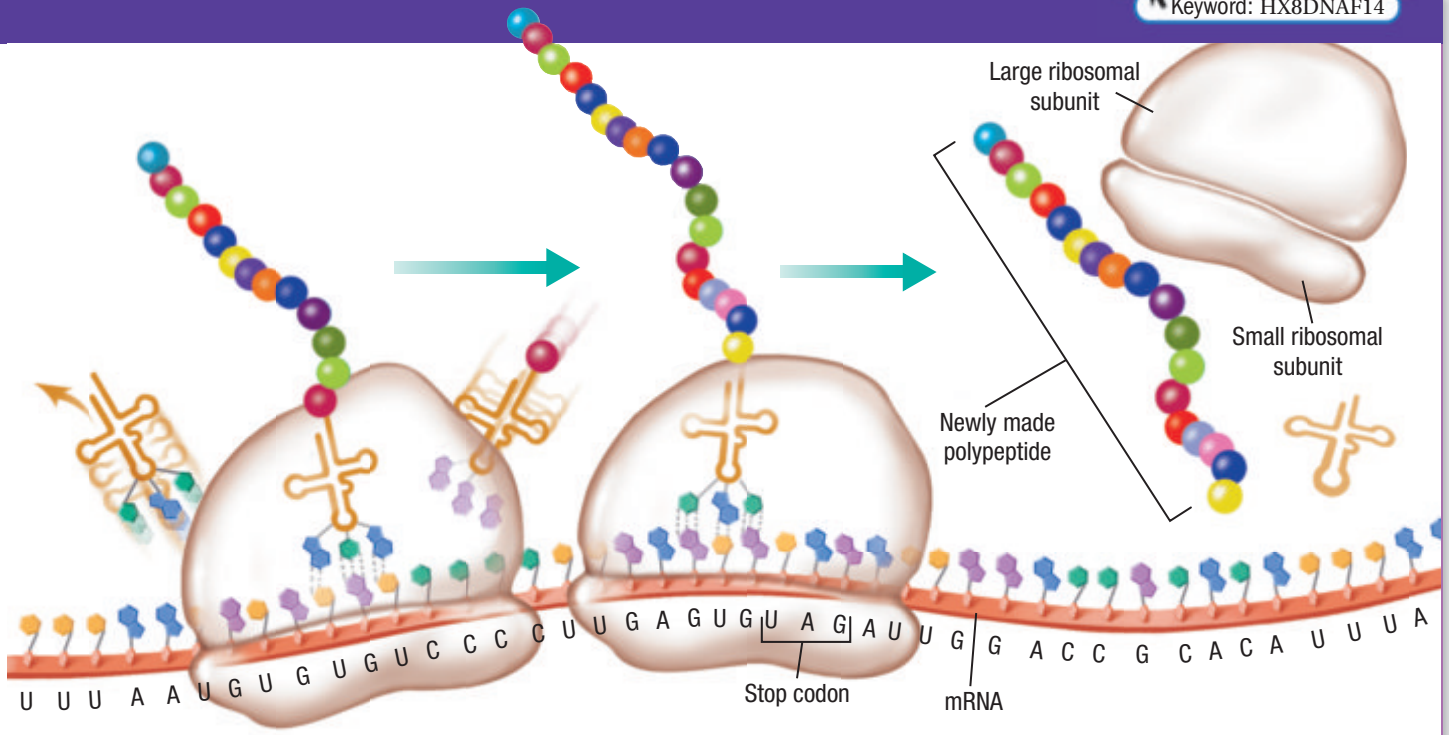


3 The first tRNA detaches and leaves its amino acid. With each new tRNA, the amino acid chain grows.

4 The process ends when a stop codon is reached.

5 The amino acid chain is released, and the ribosome complex falls apart.

Step 3 The ribosome moves one codon down the mRNA. Because the anticodon remains attached to the codon, the tRNA molecule and the mRNA molecule move as a unit, which leaves the next mRNA codon open and ready to receive the next tRNA and its amino acid. The amino acid chain continues to grow as each new amino acid binds to the chain and the previous tRNA is released.

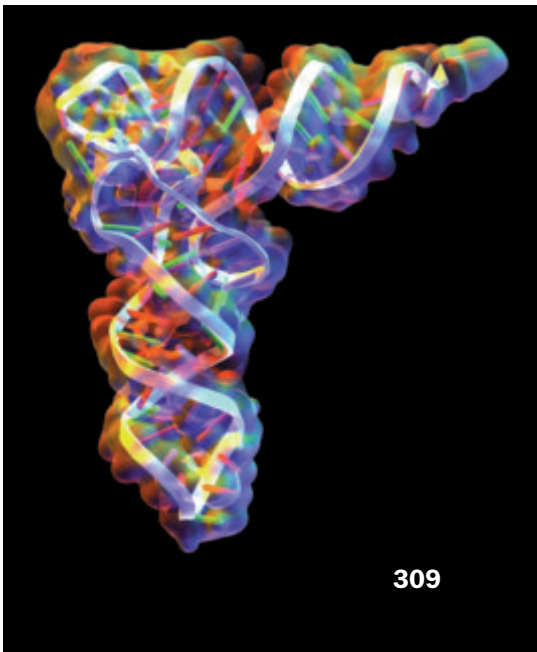
Step 4 This process is repeated until a stop codon is reached. A *stop codon* is one of three codons: UAG, UAA, or UGA. No tRNAs have anticodons for these stop codons, so protein production stops.

Step 5 The newly made polypeptide falls off the ribosome. The ribosome complex falls apart. The last tRNA leaves the ribosome, and the ribosome moves away from the mRNA. The ribosome is then free to begin translation again on the same mRNA or on another mRNA.

Repeating Translation Like replication, translation needs to happen quickly and often. As a segment of mRNA moves through a ribosome, another ribosome can form on the AUG codon on the same mRNA segment and can begin a new translation process. Thus, several ribosomes can translate the same mRNA at the same time, which allows many copies of the same protein to be made rapidly from a single mRNA molecule.

› **Reading Check** ***How do codons and anticodons differ?***

Figure 15 tRNA folds into this shape such that an anticodon is on one end and a binding site for amino acids is on the other end.



Data

QuickLab

15 min

Genetic Code of Keratin

Keratin is one of the proteins in hair. The gene for keratin is transcribed and translated by certain skin cells. The sequence below is part of the mRNA molecule that is transcribed from the gene for keratin.

Analysis

1. **Determine** the sequence of amino acids that will result from the translation of the segment of mRNA above. Use the genetic code in **Figure 13.**
2. **Determine** the anticodon of each tRNA molecule that will bind to this mRNA segment.
3. CRITICAL THINKING **Recognizing Patterns** Determine the sequence of nucleotides in the segment of DNA from which this mRNA strand was transcribed.
4. CRITICAL THINKING **Recognizing Patterns** Determine the sequence of nucleotides in the segment of DNA that is complementary to the DNA segment that is described in item 3.

Complexities of Gene Expression

The relationship between genes and their effects is complex. Despite the neatness of the genetic code, every gene cannot be simply linked to a single outcome. Some genes are expressed only at certain times or under specific conditions. Some traits result from the expression of multiple genes. Variations, mistakes, feedback, and other complex interactions can occur at each of the steps in replication and expression. The final outcome of gene expression is affected by the environment of the cells, the presence of other cells, and the timing of gene expression.

Overall, knowledge of the basic process of gene expression has allowed scientists to better understand the workings of all organisms. The next chapters delve into the exciting results of applying this knowledge.

Section 3 Review

KEY IDEAS

1. **Describe** gene expression.
2. **Explain** the role of RNA in gene expression.
3. **Summarize** transcription.
4. **Explain** how codons determine the amino acid sequence of a protein.
5. **Describe** the steps of translation.
6. **Identify** a complexity of gene expression.

CRITICAL THINKING

7. **Inferring Relationships** Multiple codons can produce the same amino acid. What is the advantage of this redundancy?
8. **Relating Concepts** What amino acid is coded for by the mRNA codon CCU?

ALTERNATIVE ASSESSMENT

9. **Gene Poster** Research two methods used to sequence the nucleotides in a gene. Compare the two methods. Give examples of how this technology might be used in a clinical setting. Prepare a poster to summarize the two methods that you researched.

Chapter 13 Summary

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SUPER SUMMARY
Keyword: HX8DNAS

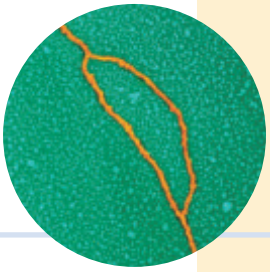
Key Ideas

1 The Structure of DNA

- DNA is the primary material that causes recognizable, inheritable characteristics in related groups of organisms.
- Three major experiments led to the conclusion that DNA is the genetic material in cells. These experiments were performed by Griffith, Avery, Hershey, and Chase.
- A DNA molecule is shaped like a spiral staircase and is composed of two parallel strands of linked subunits.
- The information in DNA is contained in the order of the bases, while the base-pairing structure allows the information to be copied.
- Watson and Crick used information from experiments by Chargaff, Wilkins, and Franklin to determine the three-dimensional structure of DNA.

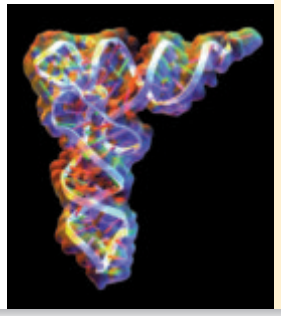
2 Replication of DNA

- In DNA replication, the DNA molecule unwinds, and the two sides split. Then, new bases are added to each side until two identical sequences result.
- The replication of DNA involves many proteins that form a machinelike complex of moving parts.
- In prokaryotic cells, replication starts at a single site. In eukaryotic cells, replication starts at many sites along the chromosome.



3 RNA and Gene Expression

- Gene expression produces proteins by transcription and translation. This process takes place in two stages, both of which involve RNA.
- In cells, three types of RNA complement DNA and translate the genetic code into proteins.
- During transcription, the information in a gene is transcribed, or copied, into mRNA.
- The genetic code is based on codons that each represent a specific amino acid.
- Translation occurs in a sequence of steps, involves three kinds of RNA, and results in a complete polypeptide.
- Despite the neatness of the genetic code, every gene cannot be simply linked to a single outcome.



Key Terms

gene (293)
DNA (293)
nucleotide (296)
purine (297)
pyrimidine (297)

DNA replication (300)
DNA helicase (301)
DNA polymerase (301)

RNA (304)
gene expression (304)
transcription (305)
translation (305)
codon (307)