Section 2 The Structure of DNA

Objectives

- **Describe** the three components of a nucleotide.
- **Develop** a model of the structure of a DNA molecule.
- **Evaluate** the contributions of Chargaff, Franklin, and Wilkins in helping Watson and Crick determine the double-helical structure of DNA.
- **Relate** the role of the base-pairing rules to the structure of DNA.

Key Terms

double helix
nucleotide
deoxyribose
base-pairing rules
complementary base pair

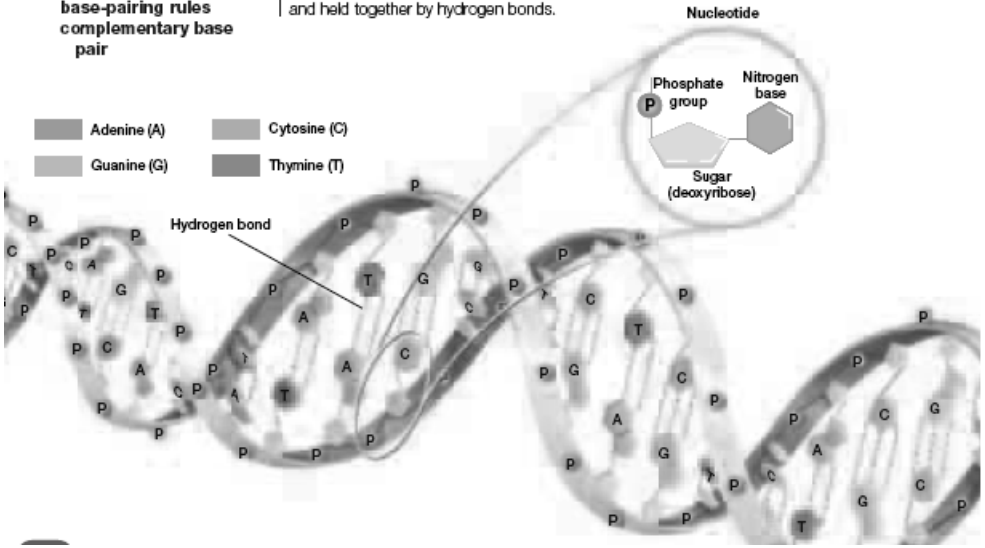
A Winding Staircase

By the early 1950s, most scientists were convinced that genes were made of DNA. They hoped that the mystery of heredity could be solved by understanding the structure of DNA. The research of many scientists led two young researchers at Cambridge University, James Watson and Francis Crick, to piece together a model of the structure of DNA. The discovery of DNA's structure was important because it clarified *how* DNA could serve as the genetic material.

Watson and Crick determined that a DNA molecule is a **double helix**—two strands twisted around each other, like a winding staircase. As shown in Figure 4, each strand is made of linked nucleotides *(NOO klee oh tiedz)*. **Nucleotides** are the subunits that make up DNA. Each nucleotide is made 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 five-carbon sugar in DNA nucleotides is called **deoxyribose** *(dee ahk see RIE bohs)*, from which DNA gets its full name, deoxyribonucleic acid.

Figure 4 DNA double helix

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



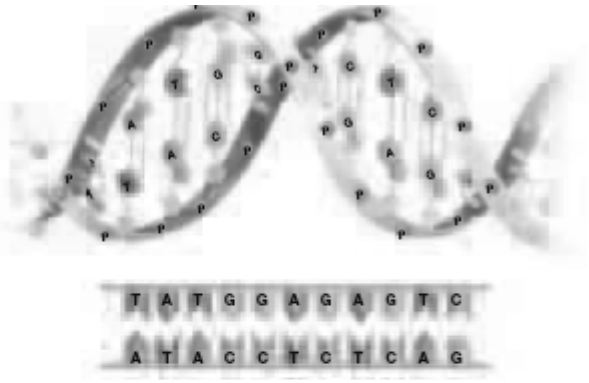


Figure 8 Base-pairing in DNA

The diagram of DNA below the helix makes it easier to visualize the base-pairing that occurs between DNA strands

Pairing Between Bases

Watson and Crick determined that a purine on one strand of DNA is always paired with a pyrimidine on the opposite strand, as you can see in **Figure 8.** More specifically, an adenine on one strand always pairs with a thymine on the opposite strand, and a guanine on one strand always pairs with a cytosine on the opposite strand. The structure and size of the nitrogen bases allows for only these two paired combinations. These **base-pairing rules** are supported by Chargaff's observations. One easy way to visualize base-pairing is by simplifying the way in which DNA structure is represented, as shown in Figure 8.

Adenine forms two hydrogen bonds with thymine, and cytosine forms three hydrogen bonds with guanine. The hydrogen bonds between the nitrogen bases keep the two strands of DNA together. The strictness of base-pairing results in two strands that contain **complementary base pairs.** That is, the sequence of bases on one strand determines the sequence of bases on the other strand. For example, if the sequence of nitrogen bases on one strand of a DNA molecule is TCGAACT, the sequence of nitrogen bases on the other strand must be AGCTTGA.

Study TIP

Organizing Information
Create a timeline that summarizes the people events that led to the discovery that DNA is the molecule where genetic information is stored. Start with 1928, and end with 1953.

Section 2 Review

1. **Describe** the three parts of a DNA nucleotide.
2. **Relate** the base-pairing rules to the structure of DNA.
3. **Descibe** the two pieces of information from other scientists that enabled James Watson and Francis Crick to discover the double-helical structure of DNA.
4. **Explain** why the two strands of the double helix are described as complementary.
5. **Critical Thinking Applying Information** Suppose a strand of DNA has the nucleotide sequence CCAGATTG. What is the nucleotide sequence of the complementary strand?
6. **Standardized Test Prep** Which pattern shows how bases pair in complementary strands of DNA?

A A-C and T-G
B A-T and C-G
C A-G and T-C
D A-A and C-C

Section 3 The Replication of DNA

Objectives

- **Summarize** the process of DNA replication.
- **Describe** how errors are corrected during DNA replication.
- **Compare** the number of replication forks in prokaryotic and eukaryotic DNA.

Key Terms

DNA replication
DNA helicase
replication fork
DNA polymerase

Roles of Enzymes in DNA Replication

When the double helix structure of DNA was first discovered, scientists were very excited about the complementary relationship between the sequences of nucleotides. They predicted that the complementary structure was used as a basis to make exact copies of the DNA each time a cell divided. Watson and Crick proposed that one DNA strand serves as a template, or pattern, on which the other strand is built. Within five years of the discovery of DNA's structure, scientists had firm evidence that the complementary strands of the double helix do indeed serve as templates for building new DNA.

The process of making a copy of DNA is called **DNA replication**. DNA replication is summarized in Figure 9. Recall from your reading of earlier chapters that DNA replication occurs during the synthesis (S) phase of the cell cycle, before a cell divides.

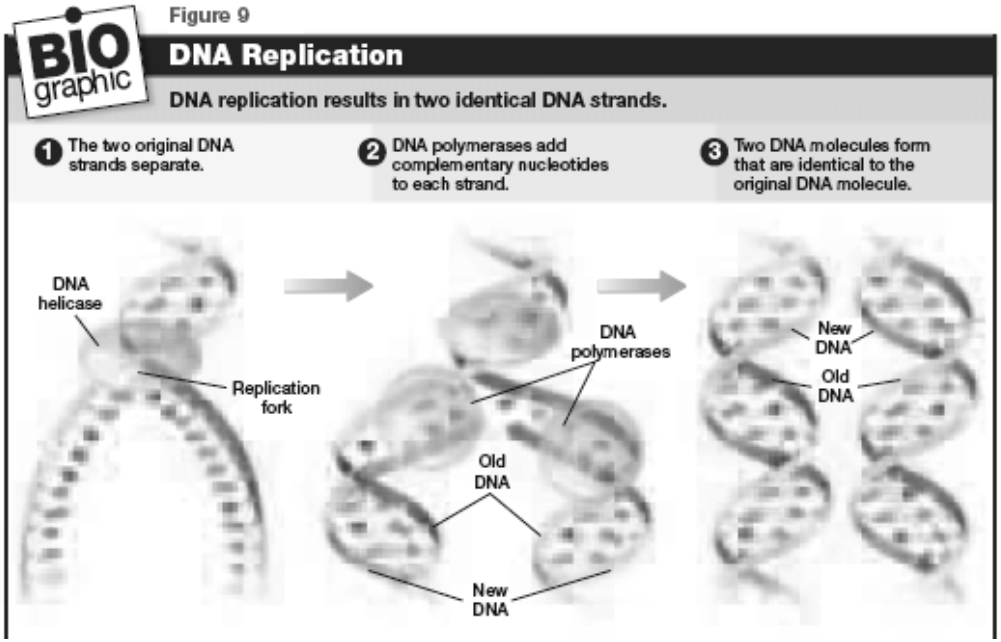
Step 1 Before DNA replication can begin, the double helix unwinds. This is accomplished by enzymes called DNA helicases. **DNA helicases** open the double helix by breaking the hydrogen bonds that link the complementary nitrogen bases between the two strands.

Figure 9

BIO graphic

DNA Replication

DNA replication results in two identical DNA strands.



Step 2 At the replication fork, enzymes known as **DNA polymerases** move along each of the DNA strands. DNA polymerases add nucleotides to the exposed nitrogen bases, according to the base-pairing rules. As the DNA polymerases move along, two new double helixes are formed.

Step 3 Once DNA polymerases have begun adding nucleotides to a growing double helix, the process continues until all of the DNA has been copied and the polymerases are signaled to detach. This process produces two DNA molecules, each composed of a new and an original strand. The nucleotide sequences in both of these DNA molecules are identical to each other and to the original DNA molecule.

Checking for Errors

In the course of DNA replication, errors sometimes occur and the wrong nucleotide is added to the new strand. An important feature of DNA replication is that DNA polymerases have a "proofreading" role. They can add nucleotides to a growing strand only if the previous nucleotide is correctly paired to its complementary base. In the event of a mismatched nucleotide, the DNA polymerase can backtrack. The DNA polymerase removes the incorrect nucleotide and replaces it with the correct one. This proofreading reduces errors in DNA replication to about one error per 1 billion nucleotides.

Section 3 Review

1. **Explain** the two roles that enzymes play in DNA replication as is illustrated in Figure 9 in this section.
2. **Explain** the relationship between DNA polymerases and mutations.
3. **State** the effect of multiple replication forks on the speed of replication in eukaryotes.
4. **Critical Thinking** **Evaluating Inform**
   If a mutation occurs during the formatio
   an egg cell or sperm cell, is that mutatio
   significant or less significant than a mut
   occurs in a body cell? Explain your answ
5. **Standardized Test Prep** How many DNA st
   exist after one molecule of DNA has been r

   A 1 **C** 4
   B 2 **D** 8

Objectives

- **Compare** the structure of RNA with that of DNA.
- **Summarize** the process of transcription.
- **Relate** the role of codons to the sequence of amino acids that results after translation.
- **Outline** the major steps of translation.
- **Discuss** the evolutionary significance of the genetic code.

Key Terms

ribonucleic acid (RNA)
uracil
transcription
translation
gene expression
RNA polymerase
messenger RNA
codon
genetic code
transfer RNA
anticodon
ribosomal RNA

Decoding the Information in DNA

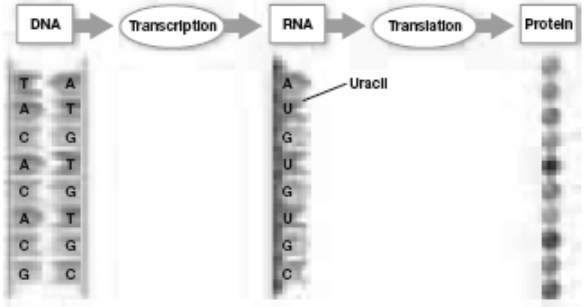
Traits, such as eye color, are determined by proteins that are built according to instructions coded in DNA. Recall that proteins have many functions, including acting as enzymes and cell membrane channels. Proteins, however, are not built directly from DNA. Ribonucleic *(rie boh noo KLAY ihk)* acid is also involved.

Like DNA, **ribonucleic acid (RNA)** is a nucleic acid—a molecule made of nucleotides linked together. RNA differs from DNA in three ways. First, RNA consists of a single strand of nucleotides instead of the two strands found in DNA, as shown in Figure 1. Second, RNA nucleotides contain the five-carbon sugar ribose *(RIE bohs)* rather than the sugar deoxyribose, which is found in DNA nucleotides. Ribose contains one more oxygen atom than deoxyribose contains. And third, in addition to the A, G, and C nitrogen bases found in DNA, RNA nucleotides can have a nitrogen base called **uracil** *(YUR uh sihl)*—abbreviated as U. No thymine (T) bases are found in RNA. Like thymine, uracil is complementary to adenine whenever RNA base-pairs with another nucleic acid.

A gene's instructions for making a protein are coded in the sequence of nucleotides in the gene. The instructions for making a protein are transferred from a gene to an RNA molecule in a process called **transcription**. Cells then use two different types of RNA to read the instructions on the RNA molecule and put together the amino acids that make up the protein in a process called **translation**. The entire process by which proteins are made based on the information encoded in DNA is called **gene expression**, or protein synthesis. This process is summarized in Figure 1.

Figure 1 Gene expression

The instructions for building a protein are found in a gene and are "rewritten" to a molecule of RNA during transcription. The RNA is then "deciphered" during translation.



Transfer of Information from DNA to RNA

The first step in the making of a protein, transcription, takes the information found in a gene in the DNA and transfers it to a molecule of RNA. **RNA polymerase,** an enzyme that adds and links complementary RNA nucleotides during transcription, is required. Figure 2 summarizes the steps of transcription.

Step 1 Transcription begins when RNA polymerase binds to the gene's promoter—a specific sequence of DNA that acts as a "start" signal for transcription.

Step 2 RNA polymerase then unwinds and separates the two strands of the double helix, exposing the DNA nucleotides on each strand.

Step 3 RNA polymerase adds and then links complementary RNA nucleotides as it "reads" the gene. RNA polymerase moves along the nucleotides of the DNA strand that has the gene, much like a train moves along on a track. Transcription follows the base-pairing rules for DNA replication except that in RNA, uracil, rather than thymine, pairs with adenine.

As transcription proceeds, the RNA polymerase eventually reaches a "stop" signal 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.

Real Life

Death cap mushrooms are deadly if eaten. One of the poisons in death cap mushrooms *(Amanita phalloides)* is taken up by liver cells, where the poison binds to an RNA polymerase. The poison prevents liver cells from making RNA and, thus, from making proteins. Liver failure—and death—can result.

Finding Information
Research other poisons found in Amanita *spp. and determine their methods of action.*

Figure 2

BIO graphic

Transcription: Making RNA

RNA polymerase adds complementary RNA nucleotides as it reads the gene.

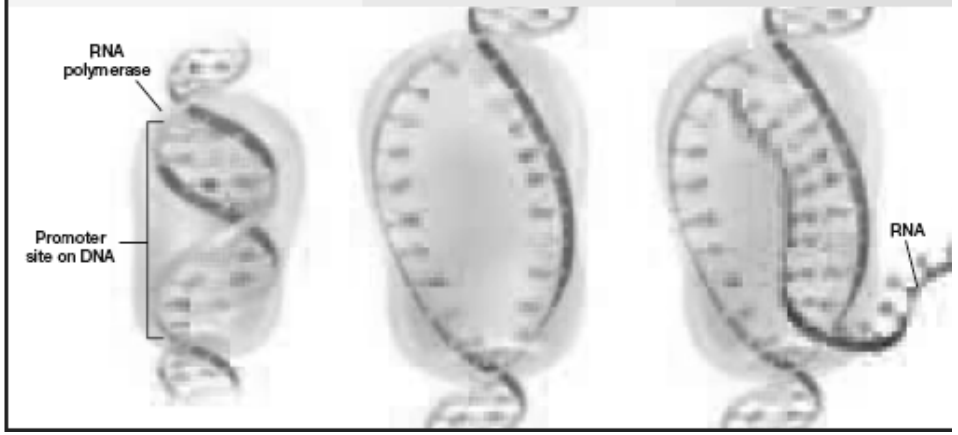


Figure 3 Multiple copies of RNA. In eukaryotes, RNA polymerase adds about 60 nucleotides per second. There are typically about 100 RNA polymerase molecules per gene.

When the RNA nucleotides are added during transcription, they are linked together with covalent bonds. As RNA polymerase moves down the strand, a single strand of RNA grows. Behind RNA polymerase, the two strands of DNA close up by forming hydrogen bonds between complementary bases, re-forming the DNA double helix.

Like DNA replication, transcription uses DNA nucleotides as a template for making a new molecule. However, in DNA replication, the new molecule made is DNA. In transcription, the new molecule made is RNA. In addition, in DNA replication, both strands of DNA serve as templates, whereas in transcription, only part of one of the two strands of DNA (a gene) serves as a template.

Transcription in prokaryotic cells occurs in the cytoplasm (because prokaryotic cells have no nucleus); transcription in eukaryotic cells occurs in the nucleus, where the DNA is located. During transcription, many identical RNA molecules are made simultaneously from a single gene, as shown in **Figure 3.** The RNA being made fans out from the gene to give a "feathery" appearance. The long line along the length of the "feather" is the DNA being transcribed. The circles along the length are the RNA polymerase molecules. The "hairs" on the feather are the RNA chains being made.

Transcription	DNA replication
RNA polymerase is used.	DNA polymerase is used.
RNA nucleotides are linked.	DNA nucleotides are linked.
An RNA molecule is made.	A DNA molecule is made.
Only one part of one strand (a gene) is used as a template.	Both DNA strands serve as templates.

The Genetic Code: Three-Nucleotide "Words"

Different types of RNA are made during transcription, depending on the gene being expressed. When a cell needs a particular protein, it is messenger RNA that is made. **Messenger RNA** (mRNA) is a form of RNA that carries the instructions for making a protein from a gene and delivers it to the site of translation. The information is translated from the language of RNA—nucleotides—to the language of proteins—amino acids. The RNA instructions are written as a series of three-nucleotide sequences on the mRNA called **codons** *(KOH dahnz)*. Each codon along the mRNA strand corresponds to an amino acid or signifies a start or stop signal for translation.

In 1961, Marshall Nirenberg, an American biochemist, deciphered the first codon by making artificial mRNA that contained only the base uracil (U). The mRNA was translated into a protein made up entirely of phenylalanine amino-acid subunits. Nirenberg concluded that the codon UUU is the instruction for the amino acid phenylalanine. Later, scientists deciphered the other codons. **Figure 4** shows the **genetic code**—the amino acids and "start" and "stop" signals that are coded for by each of the possible 64 mRNA codons.

Figure 4 Interpreting the genetic code

The amino acid coded for by a specific mRNA codon can be determined by following the three steps below.

1. Find the first base of the mRNA codon along the left side of the table.
2. Follow that row to the right until you are beneath the second base of the codon.
3. Move up or down in that section until you are even, on the right side of the chart, with the third base of the codon.

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

RNA's Roles in Translation

Translation takes place in the cytoplasm. Here transfer RNA molecules and ribosomes help in the synthesis of proteins. **Transfer RNA** (tRNA) molecules are single strands of RNA that temporarily carry a specific amino acid on one end. Each tRNA is folded into a compact shape and has an anticodon *(an tee KOH dahn)*. An **anticodon** is a three-nucleotide sequence on a tRNA that is complementary to an mRNA codon. As shown in Figure 5, the amino acid that a tRNA molecule carries corresponds to a particular mRNA codon.

Ribosomes, shown in Figure 5, are composed of both proteins and ribosomal RNA (rRNA). **Ribosomal RNA** molecules are RNA molecules that are part of the structure of ribosomes. A cell's cytoplasm contains thousands of ribosomes. Each ribosome temporarily holds one mRNA and two tRNA molecules. Figure 5 summarizes the process of translation:

Step 1 Translation begins when the mRNA leaves the nucleus and enters the cytoplasm. The mRNA, the two ribosomal subunits, and a tRNA carrying the amino acid methionine *(muh THIE uh neen)* together form a functional ribosome. The mRNA "start" codon AUG, which signals the beginning of a protein chain, is oriented in a region of the ribosome called the P site, where the tRNA molecule carrying methionine can bind to the start codon.

Step 2 The codon in the area of the ribosome called the A site is ready to receive the next tRNA. A tRNA molecule with the complementary anticodon arrives and binds to the codon. The tRNA is carrying its specific amino acids.

Step 3 Now both the A site and the P site are holding tRNA molecules, each carrying a specific amino acid. Enzymes then help form a peptide bond between the adjacent amino acids.

Step 4 Afterward, the tRNA in the P site detaches, leaves behind its amino acid, and moves away from the ribosome.

Step 5 The tRNA (with its protein chain) in the A site moves over to fill the empty P site. Because the anticodon remains attached to the codon, the tRNA molecule and mRNA molecule move as a unit. As a result, a new codon is present in the A site, ready to receive the next tRNA and its amino acid. An amino acid is carried to the A site by a tRNA and then bonded to the growing protein chain.

Step 6 The tRNA in the P site detaches and leaves its amino acid.

Step 7 Steps 2 through 6 are repeated until a stop codon is reached. A stop codon is one of three codons (UAG, UAA, or UGA) for which there is no tRNA molecule with a complementary anticodon. Because there is no tRNA to fit into the empty A site in the ribosome, protein synthesis stops. The newly made protein is released into the cell.

Figure 5

BIO graphic

Translation: Assembling Proteins

Amino acids are assembled from information encoded in mRNA.