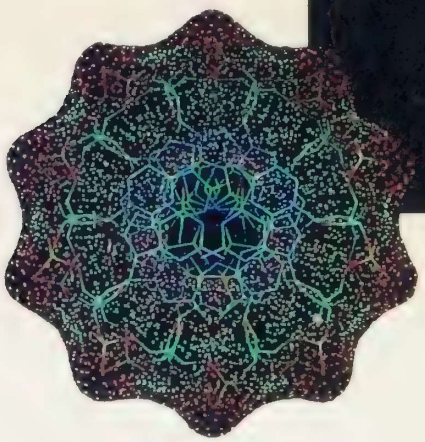
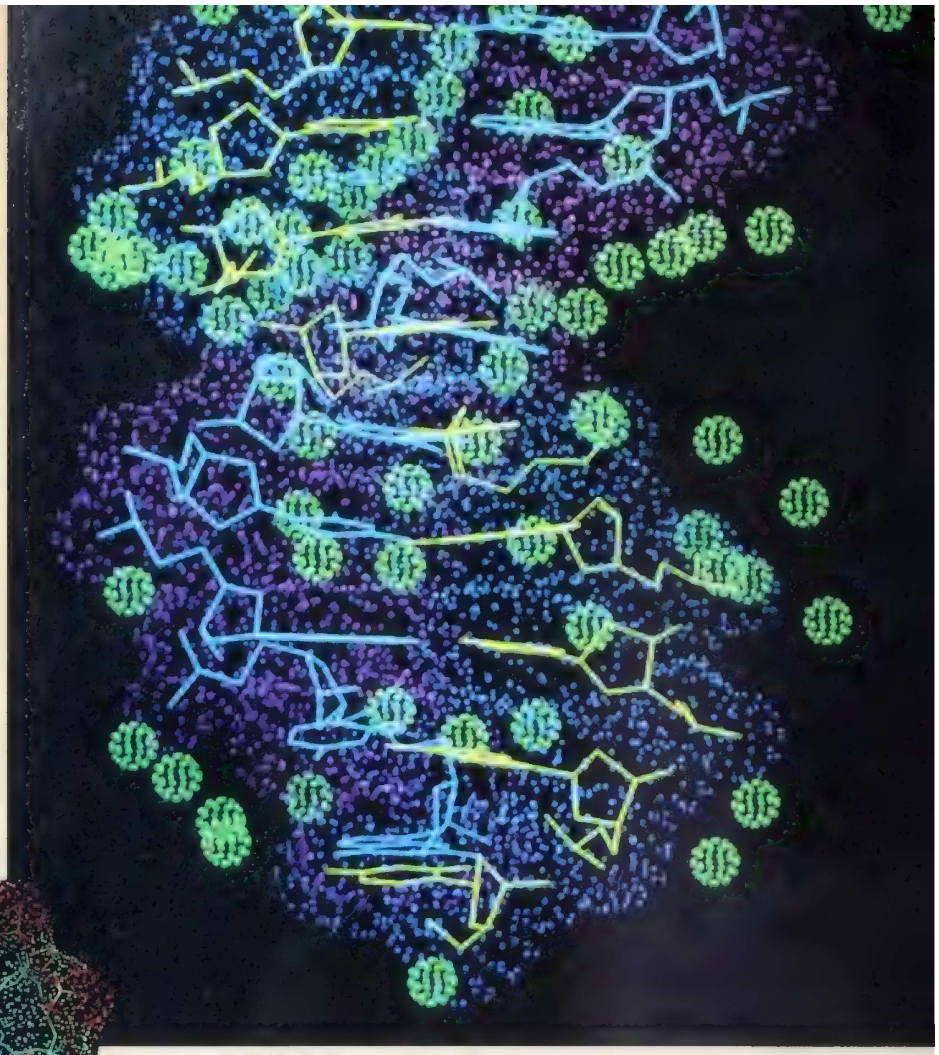
CHAPTER 7

Nucleic Acids and Protein Synthesis





The double-helical structure of DNA is shown in these computer-generated images. The larger image shows a dark-blue structure and a purple structure coiling around each other. These structures represent the two linked strands of nucleotides in DNA. The smaller image shows DNA's double helix as it appears from above.

In the middle of the twentieth century, a great revolution began to take place in biology. Like many revolutions, its beginnings were modest. Its pioneers were a handful of investigators who sought to understand how information was transferred from one generation of life to the next. The discovery that nucleic acids carry and transfer that information has altered our view of living things. In this chapter we will begin to study the nucleic acids DNA and RNA, the genetic code they contain, and the way in which that code is put into action during protein synthesis.

CHAPTER OUTLINE

7–1 DNA
- The Genetic Code
- The Structure of DNA
- The Replication of DNA

7–2 RNA
- The Structure of RNA
- Transcription: RNA Synthesis

7–3 Protein Synthesis
- The Nature of the Genetic Code
- Translation

7–1 DNA

Section Objectives

- List the contributions of various scientists to the idea that DNA carries the genetic code.
- Describe the structure and function of DNA.
- Summarize the process of DNA replication.

By now it should be clear that living cells are able to do some remarkable things. We might go so far as to say that cells "know" a great deal about the business of life: how to produce ATP, how to build cilia and centrioles, how to produce enzymes and membranes. It is as though cells are preinstructed by a code, or programmed, about what to do and how to do it.

A program, or code, in living cells must be able to duplicate itself quickly and accurately and must also have a means of being decoded and put into effect. In this chapter we will begin to learn about the nature of the cellular program—what biologists know and don't know about the ways in which the program is constructed, duplicated, and carried out.

The Genetic Code

Biologists call the program of the cell the **genetic code.** The word genetic refers to anything that relates to heredity. The genetic code, therefore, is the way in which cells store the program that they seem to pass from one generation of an organism to the next generation.

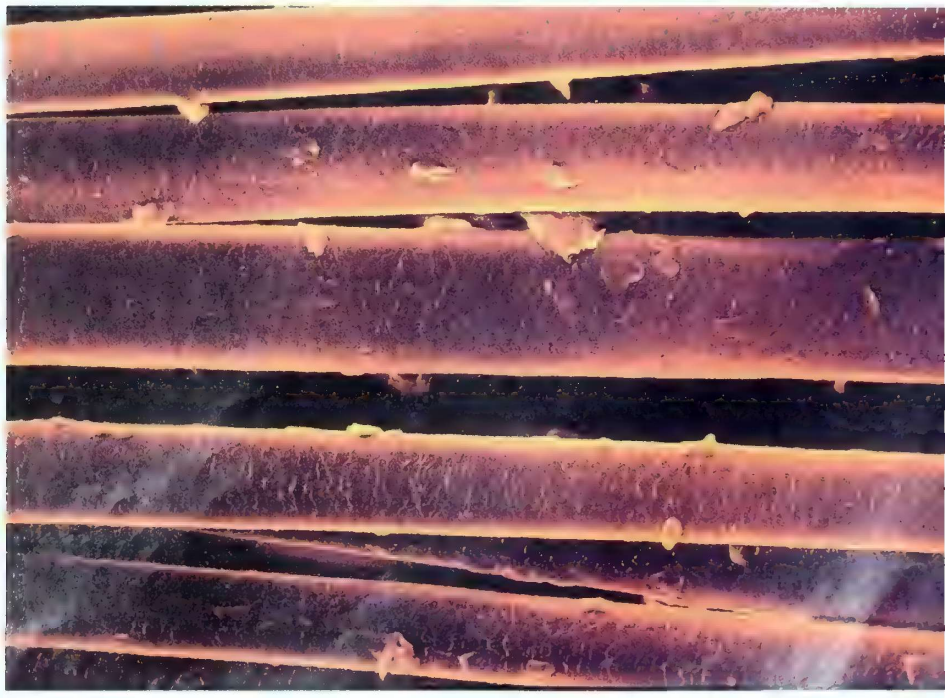


Figure 7–1 *The genetic code stores the program for making proteins, such as those that make up the strands of hair, and passes it on from generation to generation.*

Is there a molecule that carries the genetic code? As often happens in science, an opportunity to answer this question presented itself to someone who was actually interested in something else.

In 1928, the British scientist Frederick Griffith was studying the way in which certain types of bacteria cause the disease pneumonia. Griffith had in his laboratory two slightly different strains, or types, of pneumonia bacteria. Both strains grew very well in culture plates in his lab, but only one strain actually caused the disease. The disease-causing strain of bacteria grew into smooth colonies on culture plates, whereas the harmless strain produced colonies with rough edges. The differences in appearance made the two strains easy to distinguish.

When Griffith injected mice with the disease-causing strain of bacteria, the mice got pneumonia and died. When mice were injected with the harmless strain, they did not get pneumonia and they did not die. And when mice were injected with the disease-causing strain that had been killed by heat, these mice too survived. By performing this third experiment, Griffith proved to himself that the cause of pneumonia was not a chemical poison released by the disease-causing bacteria.

TRANSFORMATION Next Griffith did an experiment that produced an astonishing result. He injected mice with a mixture of live cells from the harmless strain and heat-killed cells from the disease-causing strain. To Griffith's surprise, the mice developed pneumonia!

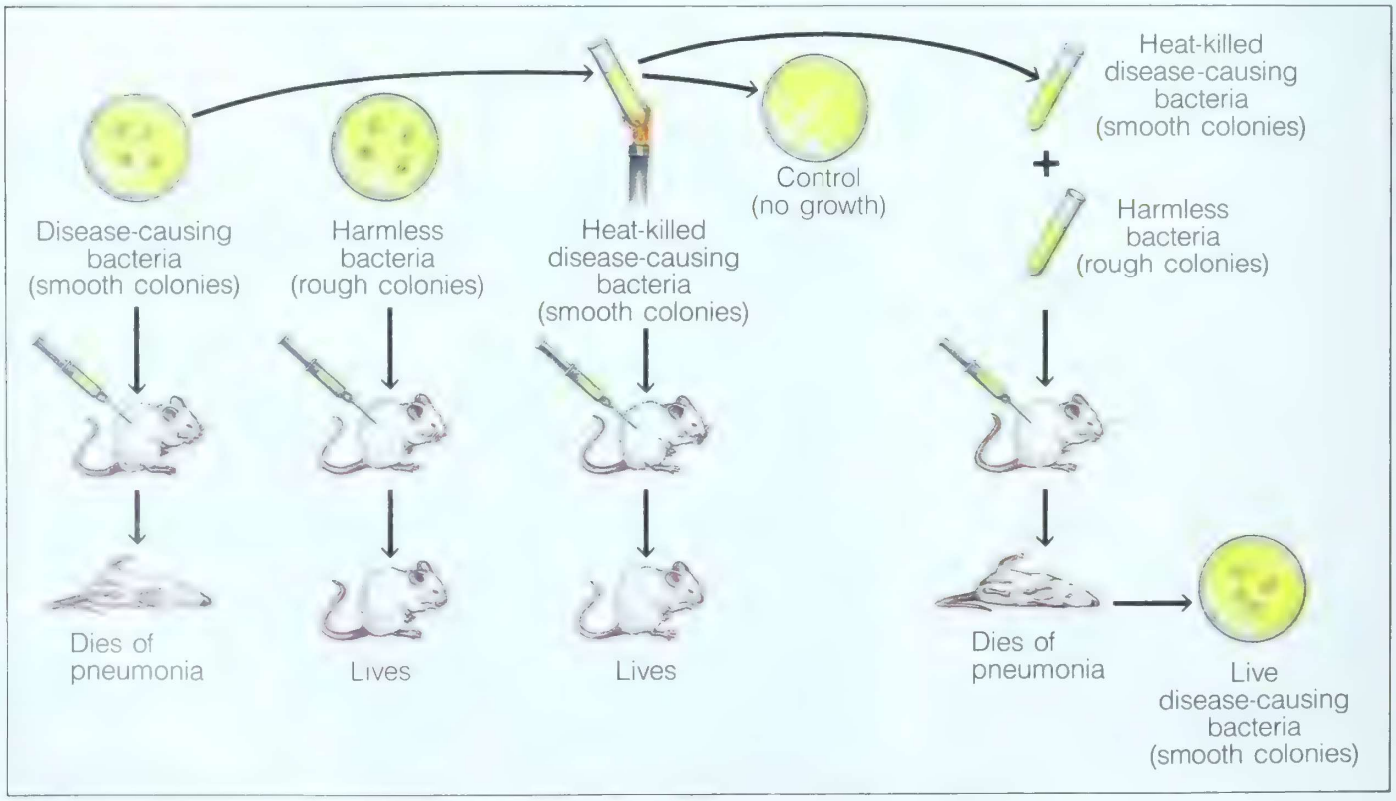


Figure 7–2 *The results of Griffith's experiments showed that "something" had been transferred from the heat-killed disease-causing bacteria to the live harmless bacteria, transforming them into live disease-causing bacteria. This something was later isolated and identified as DNA.*

Somehow Griffith's heat-killed strain had passed on its disease-causing ability to the live harmless strain. It was almost as if a farmer had scattered ground beef in a henhouse and then returned the next morning to discover that some of the eggs had begun to hatch into calves instead of baby chicks!

To confuse matters even more, Griffith recovered bacteria from the animals that had developed pneumonia. When these bacteria were grown on culture plates, they formed smooth colonies characteristic of the disease-causing strain. For all practical purposes, one strain of bacteria had been transformed into another. Griffith called this process **transformation.**

THE TRANSFORMING FACTOR Griffith theorized that when the live harmless bacteria and the heat-killed bacteria were mixed together, a factor was transferred from the heat-killed cells into the live cells. In 1944, a group of scientists at the Rockefeller Institute in New York City led by Oswald Avery, Maclyn McCarty, and Colin MacLeod decided to repeat Griffith's work and see if they could discover which molecules were Griffith's transforming factor, that is, which molecules were responsible for transformation.

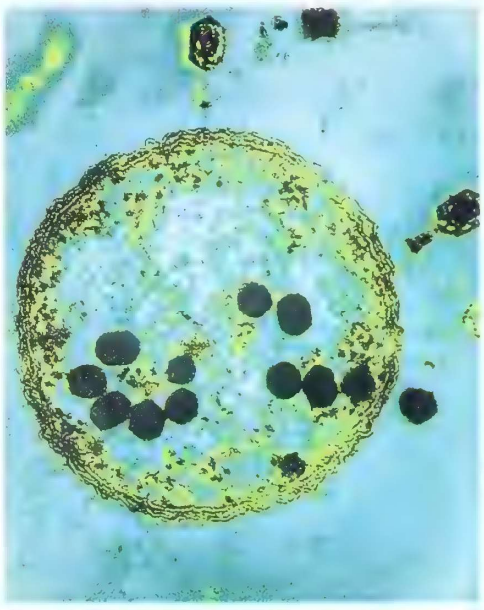
Avery and his colleagues made an extract, or juice, from the heat-killed bacteria. When they treated the extract with enzymes that destroy lipids, proteins, and carbohydrates, they discovered that transformation still occurred. Obviously these molecules were not responsible for the transformation. If they were, transformation would not have occurred because the molecules would have been destroyed by the enzymes.

Avery and the other scientists repeated the experiment, this time using enzymes that would break down RNA (ribonucleic acid). The scientists found that again transformation took place. But when they performed the experiment again, now using enzymes that would break down **DNA** (deoxyribonucleic acid), transformation did not occur. DNA was the transforming factor! **DNA is the nucleic acid that stores and transmits the genetic information from one generation of an organism to the next.** In other words, DNA carries the genetic code.

BACTERIOPHAGES The work of Avery and his colleagues clearly demonstrated the role of DNA in the transfer of genetic information. Scientists, however, are notorious for being a skeptical group, and it sometimes takes many successful experiments to convince everyone.

One of the most important of these experiments was performed in 1952 by two American scientists, Alfred Hershey and Martha Chase. Hershey and Chase were interested in the kinds of viruses that infect bacteria. Such viruses are known as bacteriophages (bak-TIHR-ee-uh-fayj-uhz), which means bacteria eaters. Bacteriophages are composed of a DNA core and a protein coat. They attach themselves to the surface of a bacterium and then inject a material into the bacterium.

Figure 7–3 *This electron micrograph shows some T-2 bacteriophages attached to the bacterium* E. coli. *Once inside, the bacteriophages take over the bacterium's DNA and instruct it to make many copies of themselves (black ovals in the bacterium).*



Once inside the bacterium, the injected material begins to reproduce, making many copies of the bacteriophage. Soon the bacterium bursts, and several hundred bacteriophages are released to infect other cells. Because the material injected into the bacterium produces new bacteriophages, it must contain the genetic code.

In their experiments, Hershey and Chase set out to learn whether the protein coat, the DNA, or both of these parts of the infecting virus was the material that entered the bacterium. First they prepared two batches of the virus. They added radioactive sulfur-35 to one batch and radioactive phosphorus-32 to the other batch. Sulfur-35 and phosphorus-32 are radioactive isotopes. You will recall from Chapter 3 that radioactive isotopes can be used as tracers to follow the pathway of certain materials.

By adding the radioactive isotopes to the viruses, Hershey and Chase were "labeling" the viruses' protein and DNA. The protein was labeled with sulfur-35, and the DNA was labeled with phosphorous-32. This was an excellent strategy because proteins contain little or no phosphorous, whereas DNA does not contain sulfur. If sulfur-35 was found in the bacteria, it would mean that the viruses' protein was injected into the bacteria. If phosphorous-32 was found in the bacteria, then it was the DNA that had been injected.

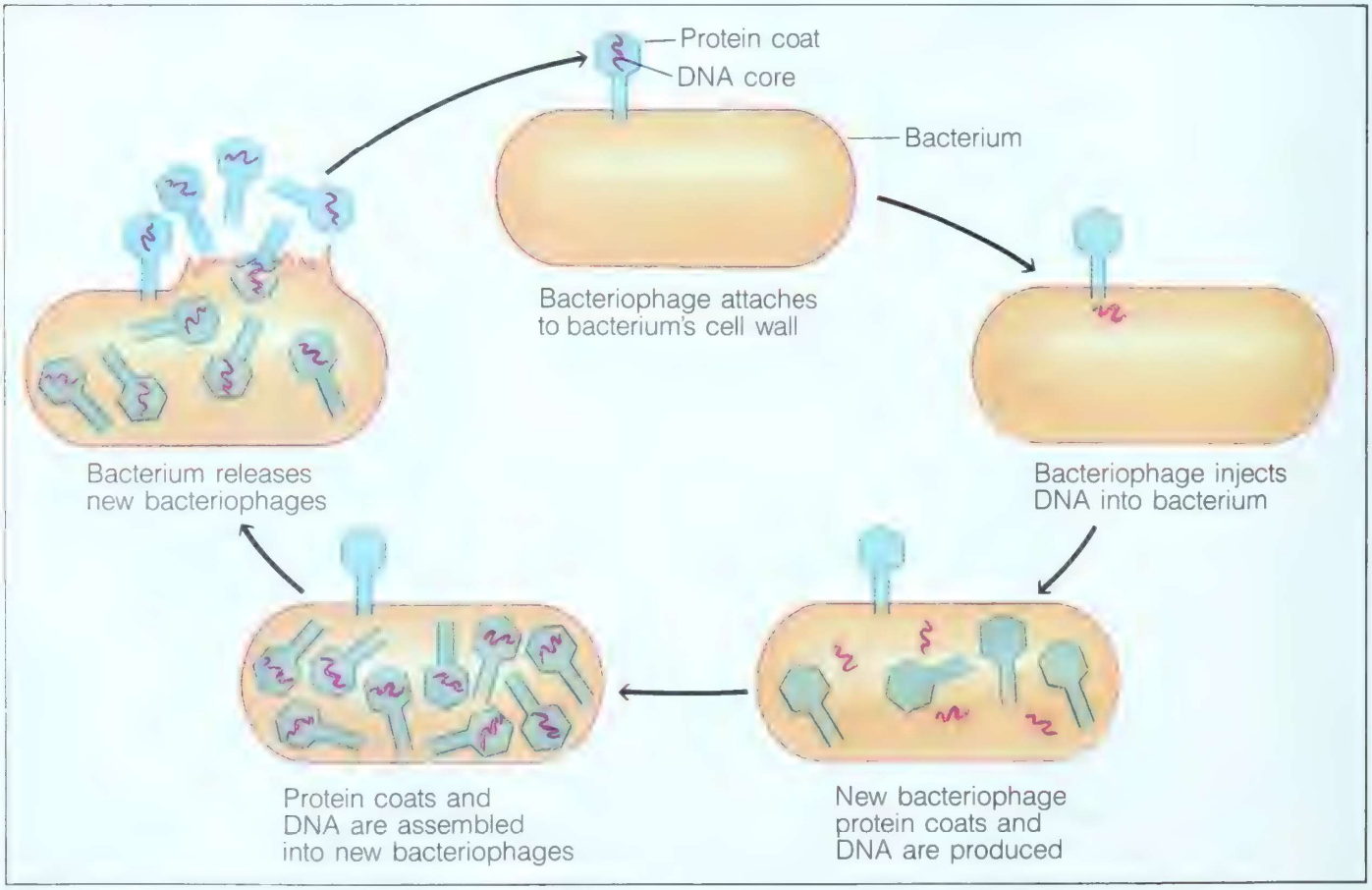


Figure 7–4 *As a result of their experiments, Hershey and Chase discovered that the DNA of a bacteriophage is injected into a bacterium, whereas the bacteriophage's protein coat remains outside the bacterium. New bacteriophages are produced inside the bacterium, indicating that DNA, not the protein, is the hereditary material of the bacteriophage.*

The two scientists mixed the radioactively labeled viruses with the bacteria. They waited a few minutes for the viruses to attach and inject the genetic material. Then they separated the viruses from the bacteria by placing the mixture in a mechanical blender and then centrifuging the mixture.

Hershey and Chase discovered that nearly all the radioactive sulfur remained within the viruses. By contrast, nearly all the radioactive phosphorous had entered the bacteria!

From these results, it was clear that the viruses' DNA enters the bacteria, and the protein coats remain outside the bacteria. This was convincing evidence that DNA contains the genetic information. When considered along with the earlier experiments on the transformation of pneumonia bacteria, the Hershey-Chase experiments showed conclusively that DNA was the molecule that carried the genetic code.

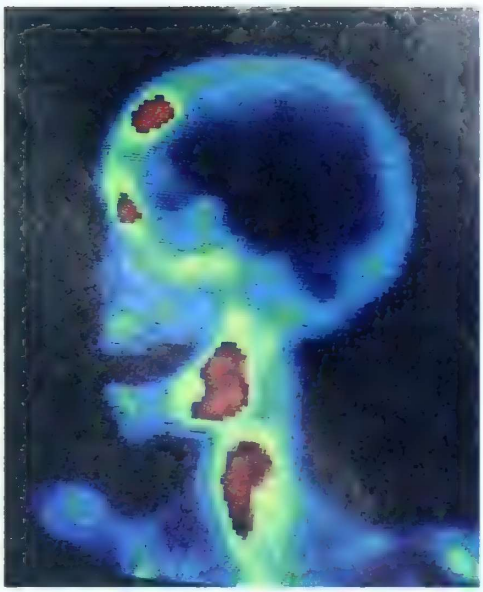


Figure 7–5 *Radioactive isotopes are used not only to follow the pathway of certain materials, but also to detect the presence of some types of cancer. This photograph shows how a radioactive isotope becomes more concentrated in a cancerous part of the body, in this case in bone, than in a healthy part of the body. The cancerous part appears in red.*

The Structure of DNA

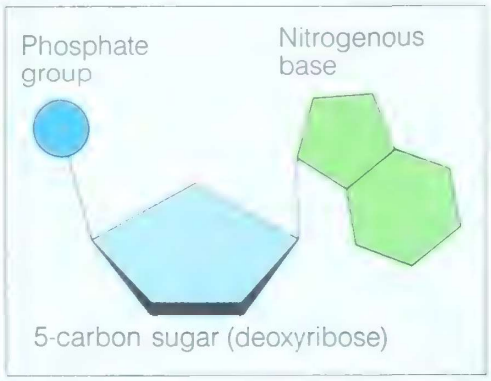
Even if DNA was shown to be the crucial molecule for the passing on of genetic information, a question of overwhelming importance remained. How could a molecule such as DNA perform two significant tasks: store information and duplicate itself easily? Let's take a look at the structure of DNA to see if that explains how it accomplishes these tasks.

As you will recall from Chapter 4, DNA is a polymer formed from units called **nucleotides.** Each nucleotide is a molecule made up of three basic parts: a 5-carbon sugar called deoxyribose (dee-ahks-ee-RIGH-bohz), a phosphate group, and a nitrogenous, or nitrogen-containing, base.

DNA contains four nitrogenous bases. Two of the nitrogenous bases, **adenine** (AD-uh-neen) and **guanine** (GWAH-neen), belong to a group of compounds known as purines (PYOOR-eenz). The remaining two, **cytosine** (SIGHT-oh-seen) and **thymine** (THIGH-meen), are known as pyrimidines (pih-RIHM-uh-deenz).

Individual nucleotides are joined together to form a long chain. Notice in Figure 7–7 on page 142 that the sugars and phosphate groups form the backbone of the chain, and the nitrogenous bases stick out from the chain.

Figure 7–6 *DNA is a polymer formed from units called nucleotides. A nucleotide is composed of three basic parts: a phosphate group, a 5-carbon sugar, and a nitrogenous base. What is DNA's 5-carbon sugar called?*



X-RAY EVIDENCE In the early 1950s, the British scientist Rosalind Franklin turned her attention to the DNA molecule. She purified a large amount of DNA and then stretched the DNA fibers in a thin glass tube so that most of the strands were parallel. Then she aimed a narrow X-ray beam on them and recorded the pattern on film. When X-rays pass through matter, they are scattered, or diffracted. This X-ray scattering produces a pattern that provides important clues to the structure of many molecules.

Franklin worked hard to prepare better and better samples until the X-ray patterns became clear. The result of her work is

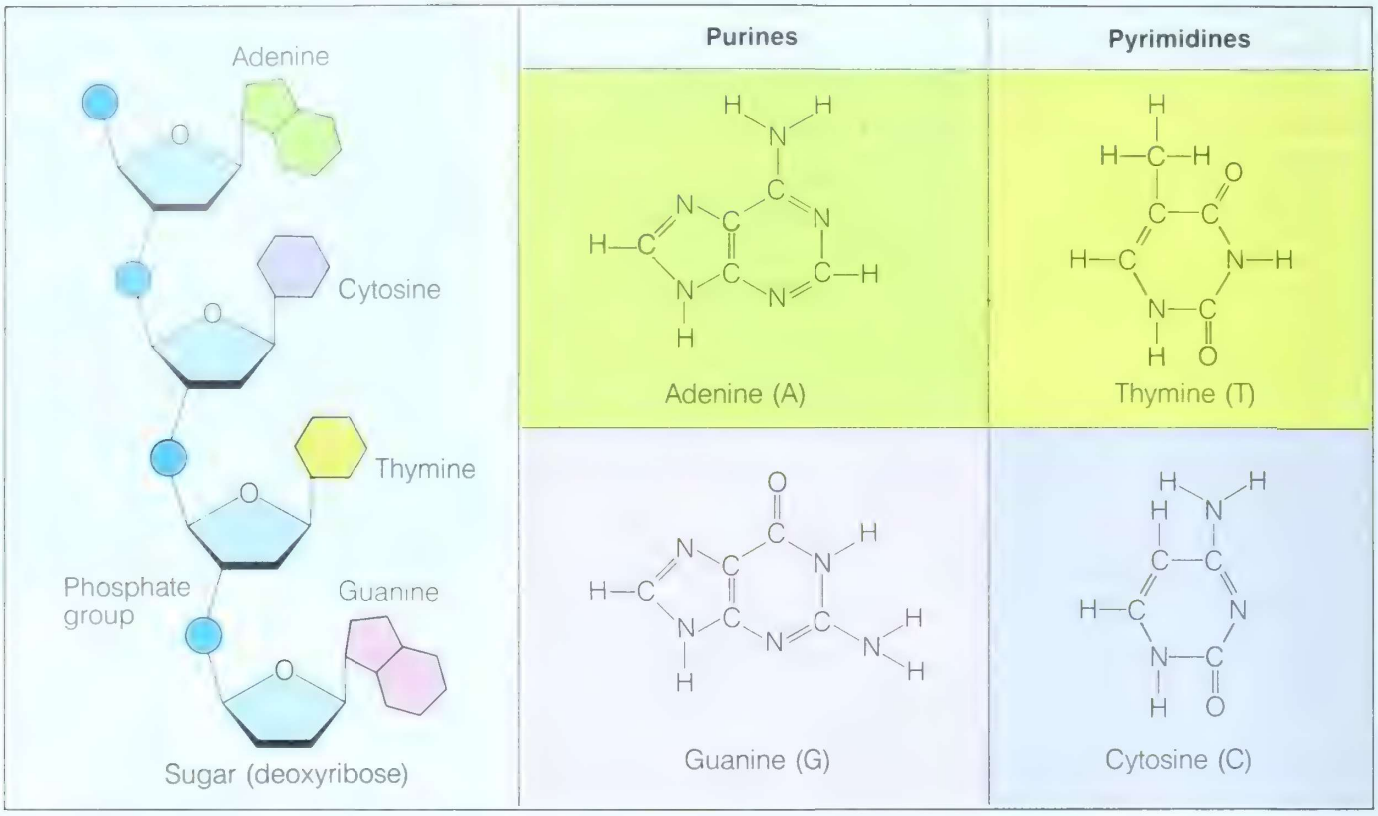


Figure 7–7 *Individual nucleotides join together to form a DNA chain. Note that each nucleotide contains one nitrogenous base.*

Figure 7–8 *This X-ray diffraction photograph of DNA was taken by Rosalind Franklin in the early 1950s. The X-shaped pattern in the center indicates that the structure of DNA is helical.*



the X-ray pattern shown in Figure 7–8. This pattern does not prove anything immediately, but it does provide some very important clues about the structure of DNA. One important clue is that the fibers that make up DNA are twisted, like the strands of a rope. This is shown by the small X near the center of the pattern. The other important clue is that large groups of molecules in the fiber are spaced out at regular intervals along the length of the fiber.

Taken alone, neither of these facts was enough to determine the structure of DNA. The X-ray pattern was like a fingerprint or a scrap of cloth at the scene of a crime. Crucial evidence, perhaps, but it would only make sense when put into a larger picture by a clever detective—or an inventive scientist!

BUILDING A MODEL OF DNA At the same time that Franklin and her colleague, Maurice Wilkins, were doing their research, two young scientists working in Cambridge, England, were also trying to determine the structure of DNA. One of the scientists was Francis Crick, a British physicist. The other was James Watson, a 25-year-old American biochemist.

Watson and Crick had been trying to solve the mystery of DNA structure by building three-dimensional models of the atomic groups in DNA. They twisted and stretched the models in various ways to see if any of the structures that formed made any sense. Watson and Crick had some interesting ideas, but nothing to test them against.

Then, during a visit to London, Watson was able to observe Franklin's remarkable X-ray pattern of DNA. At once Watson and Crick realized that there was something important in that pattern. They immediately set out to use the clues that Franklin had provided. Within weeks, Watson and Crick had figured out the structure of DNA.

THE DOUBLE HELIX Working with these clues, Watson and Crick began, quite literally, to play with their models of the DNA fiber. What they needed to do was to twist their model into a shape that would account for Franklin's X-ray pattern. Before long, they developed a shape that seemed to make sense. They called this shape a helix because it was similar to a spiral, or the way in which the threads are arranged in a screw. Using Franklin's idea that there were probably two strands of DNA, Watson and Crick imagined that the strands were twisted around each other, forming a double helix.

Watson and Crick's model explained one more characteristic about DNA's structure. The nitrogenous bases on each of the strands of DNA are positioned exactly opposite each other. This positioning allows weak hydrogen bonds to form between the nitrogenous bases adenine (A) and thymine (T), and between cytosine (C) and guanine (G).

Another interesting piece of information that helped Watson and Crick in working out their model of DNA's structure was provided by Erwin Chargaff, an American biochemist. Chargaff observed that in any sample of DNA, the number of adenine molecules was equal to the number of thymine molecules. The same was true for the number of cytosine and guanine molecules. Chargaff's observation enabled Watson and Crick to determine that adenine only bonds to thymine and cytosine only bonds to guanine. The two scientists further reasoned that the attraction of these bases for each other is very specific. The attraction between such bases is known as **base pairing.** Base pairing is the force that holds the two strands of the DNA double helix together. As you can see, Watson and Crick set out to solve one puzzle and found the answer to another puzzle too!

In 1953, after making careful drawings of their model of DNA, Watson and Crick submitted their findings to a scientific journal. Their model, although speculative in some areas, was almost immediately accepted by scientists the world over. Why? Because, as we will see, it contained a feature that explained a great mystery: how DNA could copy itself!

The importance of this work on DNA was acknowledged in 1962 by the awarding of the Nobel prize for medicine or physiology—the highest prize the international community can give for a scientific discovery—to its discoverers. Because Rosalind Franklin had died in 1958 and Nobel prizes are given only to living scientists, the prize was shared by Watson, Crick, and Franklin's associate, Maurice Wilkins.

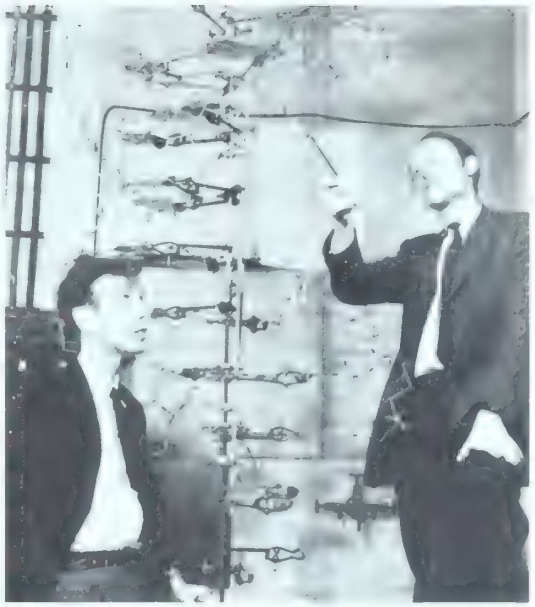


Figure 7–9 *This photograph of Watson and Crick with one of their first models of DNA was taken in 1953.*

Figure 7–10 *This three-dimensional image of DNA magnified one million times was made through a scanning tunneling microscope (STM). This recently invented microscope can distinguish individual atoms.*



The Replication of DNA

Because each of the two strands of the DNA double helix has all the information, by the mechanism of base pairing, to reconstruct the other half, the strands are said to be complementary. To illustrate this concept, we can use the analogy of a dollar bill that has been torn in half. Each half of the dollar bill tells us just what the other half must look like, even though the two halves are not identical.

Although there are four nitrogenous bases in DNA, the situation is really quite similar to that of the dollar bill. As you can see from Figure 7–11, even in a long and complicated DNA molecule, each half can specifically direct the sequence of the other half by complementary base pairing. This allows us to imagine a very simple scheme for copying the double helix, as shown in Figure 7–12. In effect, each strand of the double helix of DNA serves as a template, or pattern, against which a new strand is made.

Before a cell divides, it must duplicate its DNA. This ensures that each resulting cell will have a complete set of DNA molecules. This copying process is known as **replication.** DNA replication, or DNA synthesis, is carried out by a series of enzymes. These enzymes separate, or "unzip," the two strands of the double helix, insert the appropriate bases, and produce covalent sugar-phosphate links to extend the growing DNA chains. The enzymes even "proofread" the bases that have been inserted to ensure that they are paired correctly.

As proposed by Watson and Crick, DNA replication begins

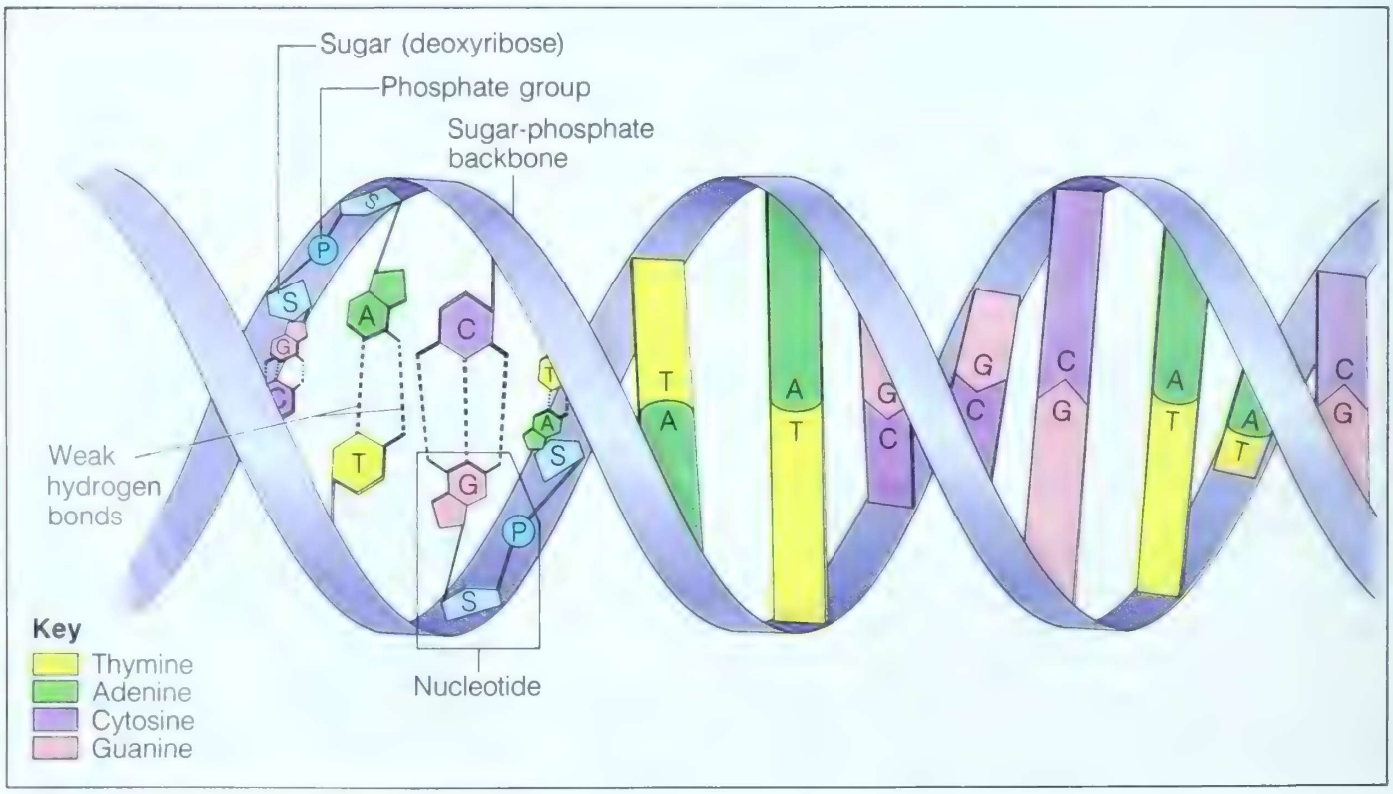


Figure 7–11 *The structure of the DNA double helix resembles a twisted ladder. The sugar-phosphate backbones form the sides of the ladder and the nitrogenous bases form the rungs of the ladder. What holds the nitrogenous bases together?*

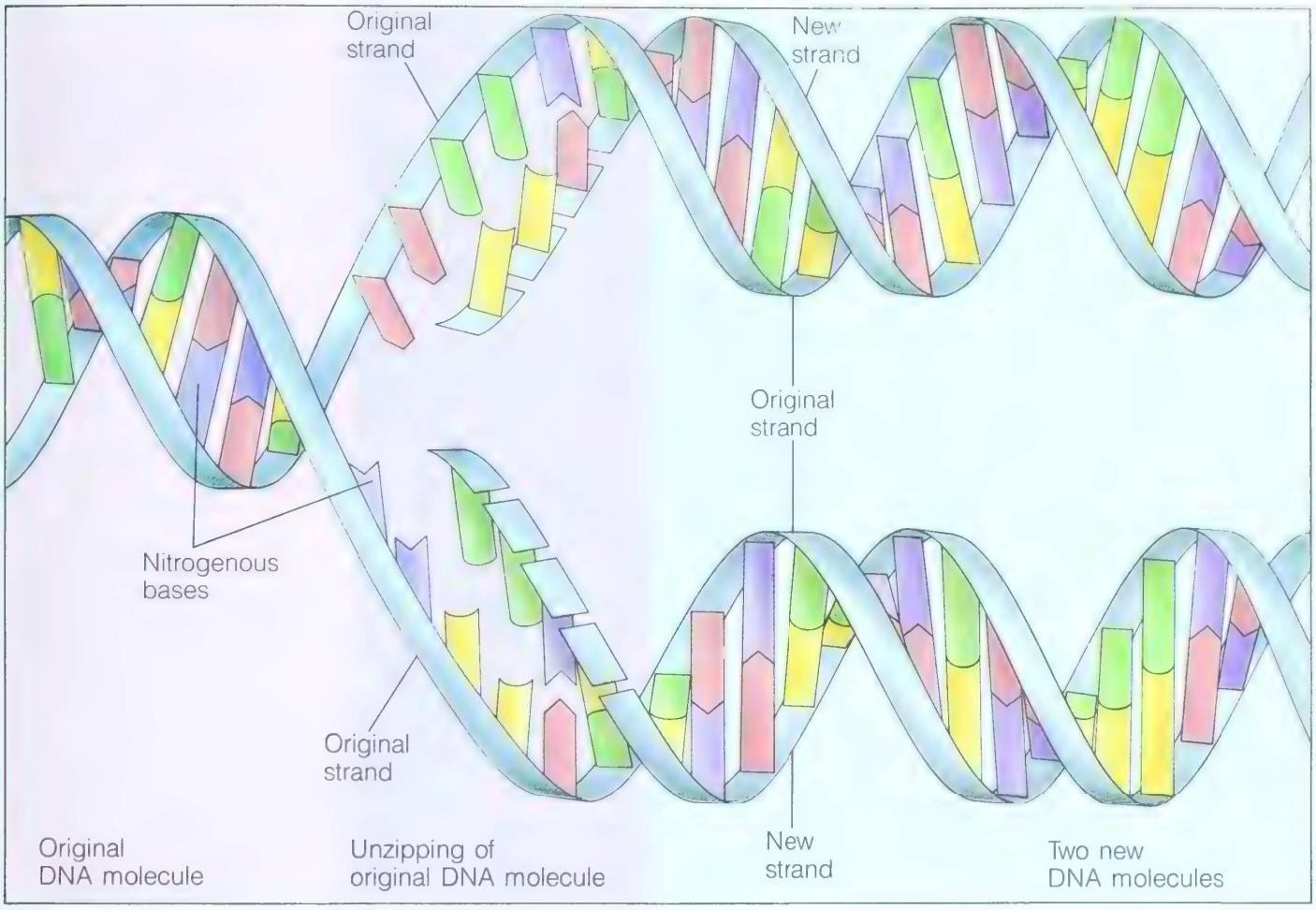


Figure 7–12 *When DNA undergoes replication, each of the original strands unzips down the middle as the base pairs separate at the hydrogen bonds. Each of the original strands serves as the template along which a new complementary strand of DNA forms.*

when a molecule of DNA "unzips." The unzipping occurs when the hydrogen bonds between the base pairs are broken and the two strands of the molecule unwind. Each of the separated strands serves as a template for the attachment of complementary bases. For example, a strand that has the bases T–A–C–G–T–T produces a strand with the complementary bases A–T–G–C–A–A. In this way, two DNA molecules identical to each other and to the original molecule are made.

7–1 SECTION REVIEW

1. Why was Griffith's work on transformation important in identifying DNA as the genetic material?
2. How did Hershey and Chase show that DNA was the molecule that carried the genetic code?
3. What is the function of DNA?
4. What are the parts of a DNA nucleotide?
5. Describe the shape of a DNA molecule.
6. Why is DNA replication necessary to life?

Section Objectives

- State the function of RNA.
- Compare the structures of RNA and DNA.
- Describe the process of transcription.

7–2 RNA

The double helix structure explains how DNA can be replicated, or copied. However, it does not explain how information is contained in the molecule or how that information is put to good use. As we will see, DNA contains a set of instructions that are coded in the sequence, or order, of nucleotides. The first step in decoding that message is to copy part of the sequence into **RNA** (ribonucleic acid). **RNA is the nucleic acid that acts as a messenger between DNA and the ribosomes and carries out the process by which proteins are made from amino acids.** As you will recall from Chapter 5, ribosomes are the organelles in which proteins are made.

The Structure of RNA

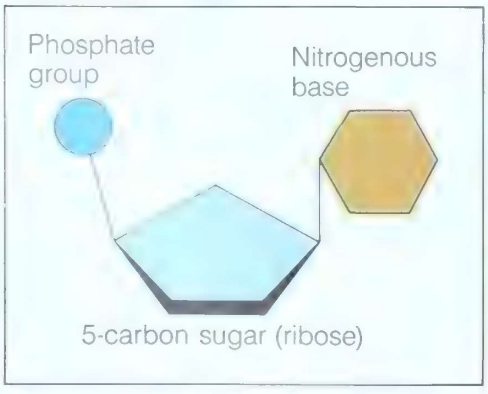
RNA, like DNA, consists of a long chain of macromolecules made up of nucleotides. Each nucleotide is made up of a 5-carbon sugar, a phosphate group, and a nitrogenous base. The alternating sugars and phosphate groups form the backbone of the RNA chain.

There are three major differences between RNA and DNA. The sugar in RNA is ribose, whereas the sugar in DNA is deoxyribose. Another difference between RNA and DNA is that RNA consists of a single strand of nucleotides, although it can form double-stranded sections by folding back on itself in loops. DNA, as you will recall, is double-stranded. Lastly, the nitrogenous bases found in DNA are adenine, thymine, cytosine, and guanine. RNA also contains adenine, cytosine, and guanine, but **uracil** (YOOR-uh-sihl) is present instead of thymine. Like DNA, RNA follows the base-pairing rules. Adenine bonds to uracil, and cytosine bonds to guanine.

Although a cell contains many different forms of RNA, there are three main types that are involved in expressing the genetic code. Each of the three main types of RNA will be discussed later in this section.

In its own way, an RNA molecule is a disposable copy of a segment of DNA. The ability to copy a DNA base sequence into RNA makes it possible for a specific place on the DNA molecule to produce hundreds or even thousands of RNA molecules with the same information as DNA.

Figure 7–13 Like DNA, RNA consists of units called nucleotides. The nucleotides in RNA, however, contain the 5-carbon sugar ribose instead of deoxyribose and the nitrogenous base uracil instead of thymine.



Transcription: RNA Synthesis

As you will recall, DNA replication is also known as DNA synthesis because the molecule being synthesized turns out to be the same as the molecule being copied. In RNA synthesis, the molecule being copied is just one of the two strands of a DNA molecule. Thus the molecule being synthesized is different from the molecule being copied. The term **transcription** is used to describe this process. **Transcription is the process by**

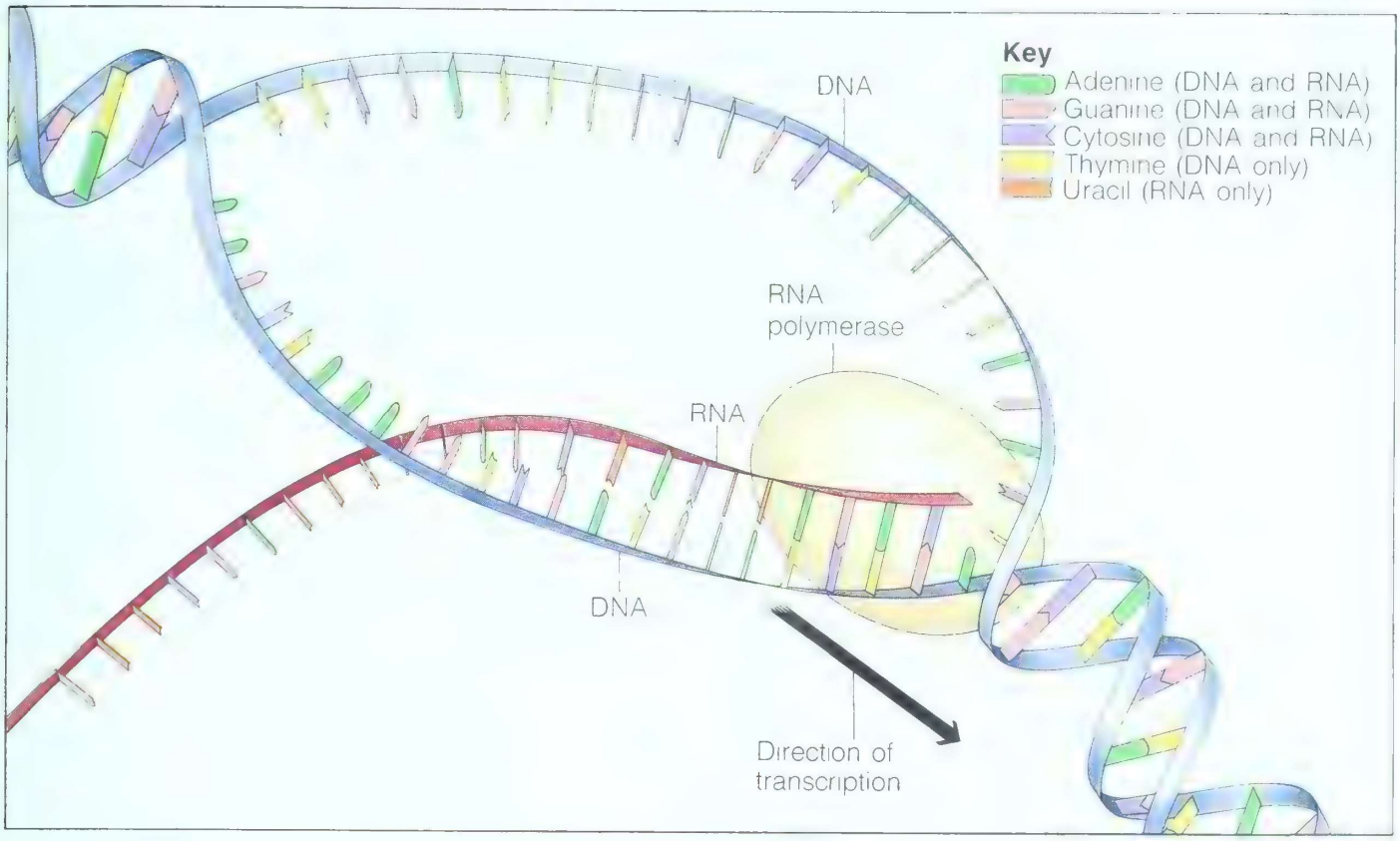


Figure 7–14 *During transcription, the enzyme RNA polymerase attaches to an area on the DNA molecule, causing it to open up. As the RNA polymerase moves along the DNA molecule, the two strands of DNA separate. Then RNA nucleotides link to the complementary bases on DNA. Which of RNA's nitrogenous bases pairs with adenine in DNA?*

which a molecule of DNA is copied into a complementary strand of RNA. In other words, transcription is the process of transferring information from DNA to RNA.

Why is it necessary for DNA to transfer its genetic information to RNA? Recall from Chapter 5 that DNA is found in the nucleus and ribosomes are located in the cytoplasm. Because DNA does not leave the nucleus, a messenger, or carrier, must bring the genetic information from the DNA in the nucleus out to the ribosomes in the cytoplasm. The molecule that performs this function is **messenger RNA** (mRNA), one of the three main types of RNA.

In order to more fully understand how transcription takes place, we must discuss the role that an enzyme known as RNA polymerase (PAHL-ih-mer-ayz) plays in this process. In Chapter 4 you learned that an enzyme is specific, that is, it works on only one substance. For this reason, part of its name is usually derived from the substance on which it works. Then the suffix *-ase* is added. Thus RNA polymerase works on the polymers RNA and DNA.

During transcription, RNA polymerase attaches to special places on the DNA molecule, separates the two strands of the double helix, and synthesizes a messenger RNA strand. The messenger RNA strand is complementary to one of the DNA strands. The base-pairing mechanism ensures that the messenger RNA will be a complementary copy of the DNA strand that serves as its template.

Special sequences in DNA serve as "start signals" and are recognized by RNA polymerase and other proteins associated with transcription. Other areas on the DNA molecule are recognized as termination sites where RNA polymerase releases the newly synthesized messenger RNA molecules.

7-2 SECTION REVIEW

1. What is the function of RNA?
2. What are three differences between RNA and DNA?
3. What is transcription?
4. Using the base-pairing rules, identify the bases on the messenger RNA strand that are transcribed from the following DNA strands: A–C–C–G–T–C–A–C; T–C–G–C–A–C–G–T.

Section Objectives

- List some of the functions of proteins in cells.
- Describe the process of translation.
- Explain the term codon.
- Identify the three main types of RNA.

7–3 Protein Synthesis

The information that DNA transfers to messenger RNA is in the form of a code. This code is determined by the way in which the four nitrogenous bases are arranged in DNA. To understand how the code works, we must answer two questions: What kind of information is contained in DNA, and how is that information decoded?

The nitrogenous bases in DNA contain information that directs protein synthesis. Why proteins and not other molecules? you might ask. The answer can be found in the diversity of things that proteins are capable of doing. Because most enzymes are proteins, proteins control biochemical pathways within the cell. Not only do proteins direct the synthesis of lipids, carbohydrates, and nucleotides, but they are also responsible for cell structure and cell movement. Like the manager of a factory, DNA does not work on the assembly line but can control what the cell factory makes by issuing orders to the organelles (workers). Together, DNA and its assistant, RNA, are directly responsible for making proteins. As you can see, DNA and RNA are like nucleic-acid executives who run the entire cell factory.

The Nature of the Genetic Code

As you will recall from Chapter 4, proteins are made by stringing amino acids together to form long chains called polypeptides. Each polypeptide contains a combination of any or all of the 20 different amino acids. How, then, can a particular order of nitrogenous bases in DNA and RNA be translated into a particular order of amino acids in a polypeptide?

Figure 7–15 *If a single nucleotide coded for one amino acid, only four amino acids could be specified (top). If two nucleotides specified for one amino acid, there could be 16 amino acids (bottom)—still not enough to code for all 20 amino acids contained in proteins.*

Four Code Letters	
A	G
C	U

Sixteen Doublets from the Four Code Letters			
AA	AC	AG	AU
CA	CC	CG	CU
GA	GC	GG	GU
UA	UC	UG	UU

As you know, DNA and RNA each contain different nitrogenous bases (DNA contains A, T, C, G; RNA contains A, U, C, G); hence, different nucleotides. For this reason, the genetic code must have a four-letter "alphabet." In order to code for the 20 different amino acids, more than one nucleotide must make up the code word for each amino acid. If code words were two nucleotides long, there would be 4^2, or 16, different code words. This is not enough for 20 amino acids. The four nucleotides arranged in triplets, or threes, however, produce 4^3, or 64, different code words. This is more than enough to produce a different code word for each amino acid. Therefore, the smallest size for a code word in DNA is three nucleotides.

The code words of the DNA nucleotides are copied onto a strand of messenger RNA. Each combination of three nucleotides on the messenger RNA is called a **codon** (KOH-dahn), or three-letter code word. **Each codon specifies a particular amino acid that is to be placed in the polypeptide chain.** See Figure 7–17. It is interesting to note that there is more than one codon for each amino acid. For example, the amino acid leucine (LOO-seen) has six different codons. There is also one codon, AUG, that can either specify the amino acid methionine (muh-THIGH-uh-neen) or serve as a starter for the synthesis of a protein. For this reason, AUG is called an "initiator" codon. Notice also that there are three "stop" codons. They do not code for an amino acid. Instead, these codons act like the period at the end of a sentence: They signify the end of a polypeptide.

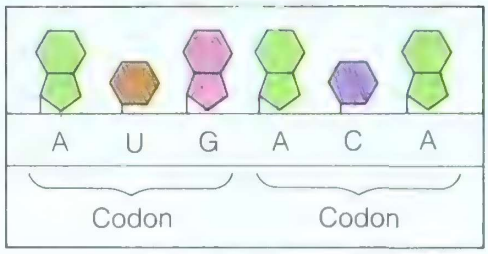
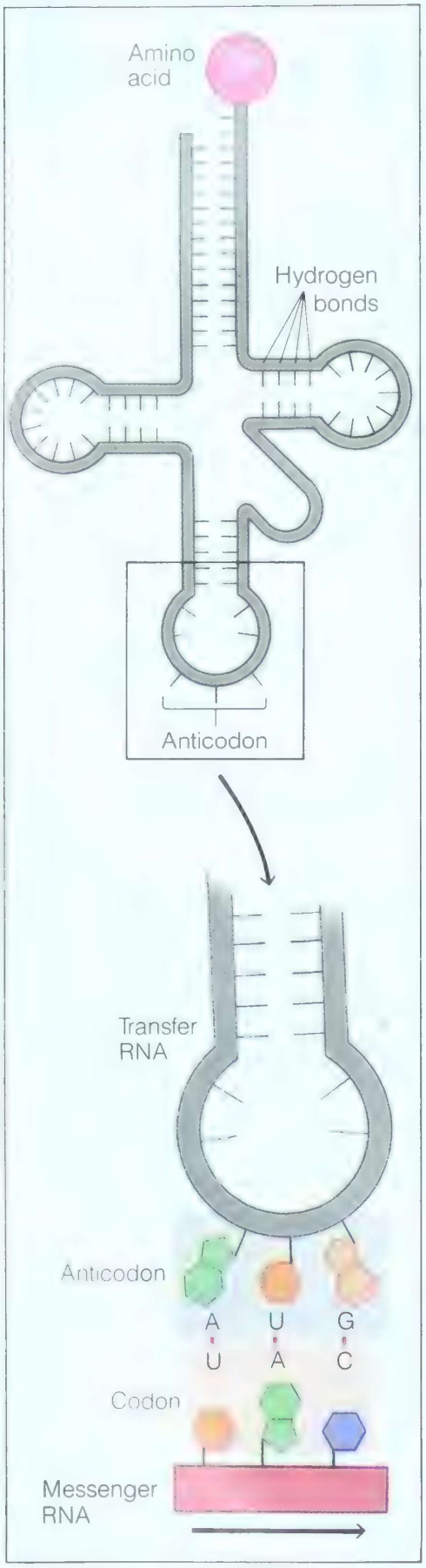


Figure 7–16 *Each combination of three nucleotides on messenger RNA is called a codon, or three-letter code word.*

First Base in Code Word	Second Base in Code Word: A	Second Base in Code Word: G	Second Base in Code Word: U	Second Base in Code Word: C	Third Base in Code Word
A	Lysine	Arginine	Isoleucine	Threonine	A
	Lysine	Arginine	Methionine	Threonine	G
	Asparagine	Serine	Isoleucine	Threonine	U
	Asparagine	Serine	Isoleucine	Threonine	C
G	Glutamic acid	Glycine	Valine	Alanine	A
	Glutamic acid	Glycine	Valine	Alanine	G
	Aspartic acid	Glycine	Valine	Alanine	U
	Aspartic acid	Glycine	Valine	Alanine	C
U	"Stop" codon	"Stop" codon	Leucine	Serine	A
	"Stop" codon	Trytophan	Leucine	Serine	G
	Tyrosine	Cysteine	Phenylalanine	Serine	U
	Tyrosine	Cysteine	Phenylalanine	Serine	C
C	Glutamine	Arginine	Leucine	Proline	A
	Glutamine	Arginine	Leucine	Proline	G
	Histidine	Arginine	Leucine	Proline	U
	Histidine	Arginine	Leucine	Proline	C

Figure 7–17 *The genetic code consists of 64 codons along with their corresponding amino acids. These codons are found on messenger RNA. Of the 64 codons, 61 specify a particular amino acid. The other three are stop codons, which signify the end of a polypeptide chain. What are the three-letter code words for each of the stop codons?*



Translation

How does a messenger RNA molecule actually produce a polypeptide? The decoding of a messenger RNA message into a polypeptide chain (protein) is known as **translation.** Translation is an appropriate word for this process because it emphasizes that the message is being translated from the language of nucleic acids into a polypeptide. The messenger RNA molecule does not produce a polypeptide by itself. Instead, there is an elaborate mechanism that involves the two other main types of RNA—**transfer RNA** (tRNA) and **ribosomal RNA** (rRNA)—and the cytoplasmic organelle known as the ribosome.

Transfer RNA carries amino acids to the ribosomes, where the amino acids are joined together to form polypeptides. Transfer RNA is a single strand of RNA that loops back on itself. See Figure 7–18. There are different transfer RNA molecules for each of the 20 amino acids. Ribosomal RNA makes up the major part of the ribosomes.

THE ROLE OF TRANSFER RNA In order to translate the information from a single codon of messenger RNA, such as AUG, we would have to find out which amino acid is coded for by AUG. Look at Figure 7–17 on page 149. As you just read, the codon AUG codes for the amino acid methionine. Methionine is then brought to the polypeptide chain by transfer RNA.

Look at Figure 7–18. You will notice that there are three exposed bases on each transfer RNA molecule. These nucleotides will base pair with a codon on messenger RNA. Because the three nucleotides on transfer RNA are complementary to the three nucleotides on messenger RNA, the three transfer RNA nucleotides are called the **anticodon.**

Attached to each transfer RNA molecule is the amino acid specified by the codon to which it base pairs. By matching the transfer RNA anticodon to the messenger RNA codon, the correct amino acid is put into place. Each transfer RNA acts like a tiny beacon for its specific amino acid.

THE ROLE OF THE RIBOSOME Messenger RNA molecules do not automatically line up transfer RNA molecules and link their amino acids together any more than model airplane parts glue themselves together automatically. Instead, this process of protein synthesis takes place in organelles known as

Figure 7–18 *Transfer RNA is a single strand of RNA that loops back on itself. Each transfer RNA molecule has two important sites of attachment. One site, called the anticodon, binds to the codon on the messenger RNA molecule. The other site attaches to a particular amino acid. During protein synthesis, the anticodon of a transfer RNA molecule base pairs with the appropriate messenger RNA codon.*

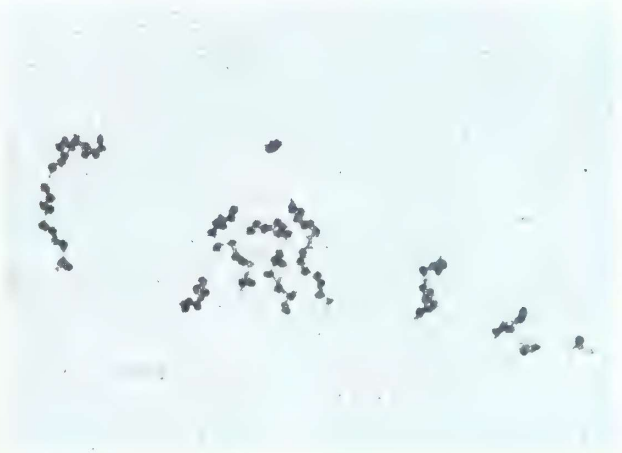
SCIENCE, TECHNOLOGY, AND SOCIETY **BREAKTHROUGH**

Seeing DNA in Action

In this chapter we have been talking about the roles of DNA and RNA in primarily eukaryotic cells, or cells that have a nucleus. However, there exist major groups of living organisms that do not have a nucleus. These organisms are called prokaryotes. Bacteria are examples of prokaryotes.

Because the DNA of a prokaryote is not tucked away in a separate compartment, there is nothing to stop protein synthesis from beginning as soon as the free end of a messenger RNA is available. This means that translation can begin at one end of a messenger RNA molecule before transcription is even completed. It is as if builders started to build one side of a house before the drawings for the other end were even completed!

Oscar Miller, a scientist at the University of Virginia, has pioneered a number of special techniques designed to allow DNA and RNA to be seen in the electron microscope in the act of translation and transcription. Miller's electron micrographs show how simultaneous transcription and translation actually take place. A strand of DNA is being made into messenger RNA at several places at once. Even before the RNA molecules have been completed, several ribosomes have attached themselves to the free ends of the RNA molecule and have begun to make polypeptides. The living cell, obviously, is in a big hurry!



This electron micrograph of E. coli *genes shows transcription and translation occurring simultaneously.*

ribosomes. Ribosomes are made up of two subunits, a large one and a smaller one. Each subunit consists of ribosomal RNA and proteins (about 70 different types).

The first part of protein synthesis occurs when the two subunits of the ribosome bind to a molecule of messenger RNA. Then the initiator codon AUG binds to the first anticodon of transfer RNA, signaling the beginning of a polypeptide chain. Soon the anticodon of another transfer RNA binds to the next messenger RNA codon. This second transfer RNA carries the second amino acid that will be placed into the chain of the polypeptide.

As each anticodon and codon bind together, a peptide bond forms between the two amino acids. You will recall from

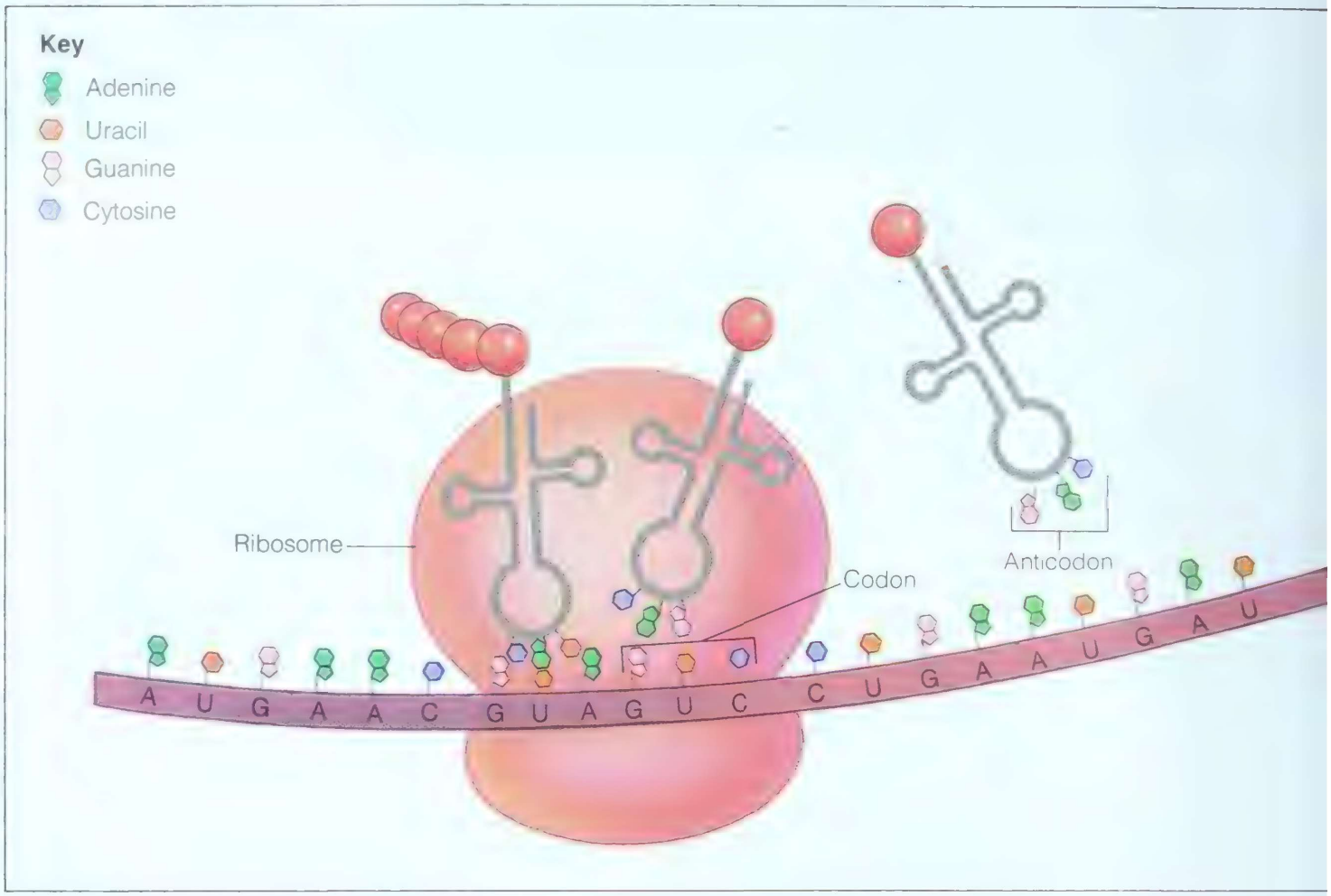
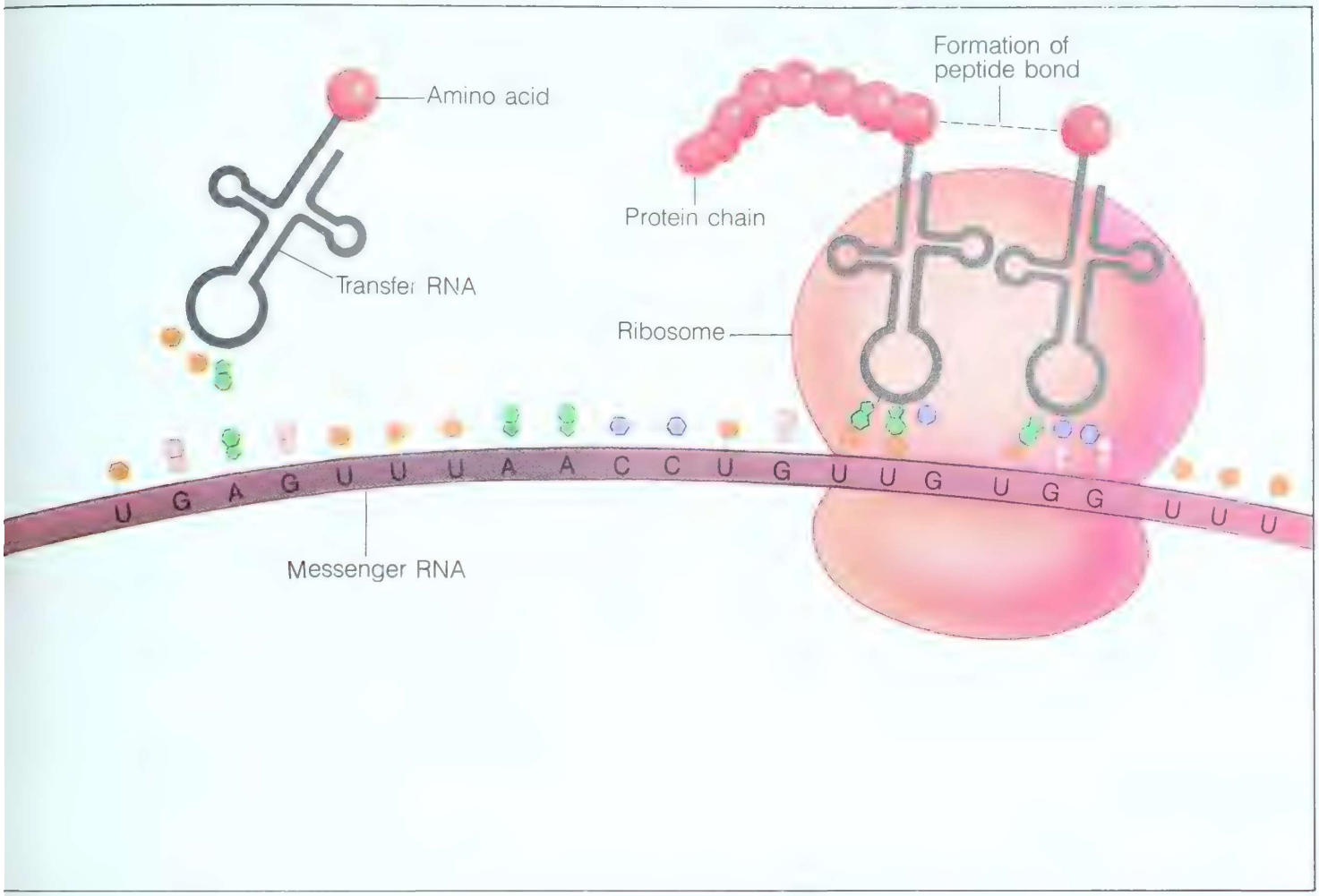


Figure 7–19 *During translation, the language of the nucleic acids (DNA and RNA) is transferred to the language of the amino acids. In which cellular organelle does this process take place?*

Chapter 4 that a peptide bond is the covalent bond that joins two amino acids together. The polypeptide chain continues to grow until the ribosome reaches a stop codon on the messenger RNA. A stop codon is a codon for which no transfer RNA molecules exist. When the stop codon reaches the ribosome, the ribosome releases the newly formed polypeptide and messenger RNA, completing the process of translation.

As you can now see, the ribosome, in its own way, is at the center of the whole business of making the genetic code work. In the nucleus, DNA directs the formation of three different kinds of RNA: transfer RNA, ribosomal RNA, and messenger RNA. They all leave the nucleus and then seem to go their separate ways. Despite these different paths, however, they all meet again in the ribosome where protein synthesis takes place. So the ribosome can be considered the place where a kind of "class reunion" of RNA molecules occurs. Here each type of RNA molecule plays a role in carrying out the instructions specified in the genetic code. And the genetic code stores the program for protein synthesis and passes it on from generation to generation.



7-3 SECTION REVIEW

1. What is translation? Transcription?
2. UAG is a stop codon. What might happen if the uracil in this codon was changed to cytosine?
3. What is a codon? An anticodon?
4. Name and give the function of the three main types of RNA molecules.
5. Why is a ribosome essential for protein synthesis?
6. What is the role of transfer RNA in translation?
7. If a code on a DNA molecule is CTA for a specific amino acid, what is the messenger RNA codon? The transfer RNA anticodon?
8. A certain protein is made up of 100 amino acids. What is the smallest number of bases in the messenger RNA molecule that is needed to carry the code for the synthesis of this protein?

LABORATORY INVESTIGATION

CONSTRUCTING A MODEL OF DNA REPLICATION

PROBLEM

How does DNA replicate?

MATERIALS *(per group)*

colored construction paper:

white	light blue
red	dark green
dark blue	light green

metric ruler
scissors
transparent tape

PROCEDURE

1. With the scissors, cut out the pieces of colored construction paper as indicated in the chart. **CAUTION:** *Be careful when using scissors.* Write the name of each part of your DNA model on the appropriate piece of construction paper.
2. To construct a model of a DNA nucleotide, tape a phosphate group, a sugar, and a guanine (G) together in the same manner as shown in Figure 7-6 on page 141. Then assemble eight additional nucleotide models with the following nitrogenous bases: T, T, A, C, A, A, T, C.

Part of DNA Model	Color	Size (cm x cm)	Number
Sugar	White	2 x 2	54
Phosphate group	Red	1 x 2	54
Adenine (A)	Dark blue	1 x 2	18
Thymine (T)	Light blue	1 x 2	18
Guanine (G)	Dark green	1 x 2	9
Cytosine (C)	Light green	1 x 2	9

3. Attach the nine nucleotide models together in the sequence given in step 2 (G, T, T, A, C, A, A, T, C) by taping the sugar on one nucleotide to the phosphate group on the next nucleotide. This will form the single strand of your DNA model.
4. Using the rules for base pairing, construct a second strand of the DNA model that is complementary to the first strand. Tape the nucleotides together as you did in step 3. Do not tape the two strands of DNA together.
5. Separate the two strands and use each to construct a new complementary strand.
6. Reassemble the original double strand of DNA. Tape this model of DNA together at its nitrogenous bases.
7. Again using the base-pairing rules, construct a complementary strand for each of the single strands of DNA you made in step 5. Tape these two new DNA models together at their nitrogenous bases. Compare the new double-stranded DNA models with your original DNA model.

OBSERVATIONS

1. What is the sequence of nitrogenous bases in the complementary strand of your original DNA model?
2. How many models of DNA did you construct from your original model of DNA? What is the base sequence for each of these new models?

ANALYSIS AND CONCLUSIONS

1. Why do you think complementary base pairing is necessary for replication?
2. Compare the base sequences of the original DNA model with the replicated models. Compare the base sequences of the replicated models.
3. If each triplet of nitrogenous bases on DNA codes for a specific amino acid, how many amino acids will your original DNA model code for?

SUMMARIZING THE CONCEPTS

The key concepts in each section of this chapter are listed below to help you review the chapter content. Make sure you understand each concept and its relationship to other concepts and to the theme of this chapter.

7–1 DNA

- DNA is the nucleic acid that stores and transmits the genetic information from one generation of an organism to the next.
- DNA is a polymer that is made up of units called nucleotides. Each nucleotide is a molecule made up of three parts: a 5-carbon sugar called deoxyribose, a phosphate group, and a nitrogenous base.
- DNA has four nitrogenous bases: adenine, thymine, cytosine, and guanine. Adenine and guanine belong to a group of compounds called purines. Thymine and cytosine belong to a group of compounds called pyrimidines.
- During replication, the DNA molecule unzips, or separates, into two strands. Each of the separated strands serves as a template, or pattern, for the attachment of complementary nucleotides.

7–2 RNA

- There are three major differences between DNA and RNA: RNA contains the sugar ribose instead of deoxyribose; RNA is usually single-stranded instead of double-stranded; and RNA contains the nitrogenous base uracil instead of thymine.
- During transcription, the DNA code is transferred to messenger RNA, which carries the code out of the nucleus into the cytoplasm.

7–3 Protein Synthesis

- During translation, messenger RNA binds to the ribosomes on which ribosomal RNA is found. Amino acids in the cytoplasm are picked up by transfer RNA and are carried to messenger RNA. The anticodons in transfer RNA attach to the proper codons in messenger RNA. Thus the messenger RNA acts as the pattern for protein synthesis. In this way, amino acids are brought together in the correct sequence to form a protein molecule.

REVIEWING KEY TERMS

Vocabulary terms are important to your understanding of biology. The key terms listed below are those you should be especially familiar with. Review these terms and their meaning. Then use each term in a complete sentence. If you are not sure of a term's meaning, return to the appropriate section and review its definition.

7–1 DNA

genetic code
transformation
DNA
nucleotide
adenine
guanine
cytosine
thymine
base pairing
replication

7–2 RNA

RNA
uracil
transcription
messenger RNA

7–3 Protein Synthesis

codon
translation
transfer RNA
ribosomal RNA
anticodon

CHAPTER REVIEW

CONTENT REVIEW

Multiple Choice

Choose the letter of the answer that best completes each statement.

1. The process of changing one strain of bacteria into another is called
   a. transformation. c. replication.
   b. translation. d. transcription.
2. DNA is a
   a. carbohydrate. c. nucleic acid.
   b. lipid. d. sterol.
3. A nucleotide of DNA would contain
   a. uracil, deoxyribose, and phosphate.
   b. phosphate, deoxyribose, and thymine.
   c. nitrogenous base, phosphate, and glucose.
   d. adenine, ribose, and phosphate.
4. Watson and Crick described the DNA molecule as a
   a. branching chain. c. single strand.
   b. straight chain. d. double helix.
5. Between which types of compounds in a double-stranded DNA molecule must the bonds break before replication takes place?
   a. phosphate–base c. adenine–thymine
   b. sugar–phosphate d. sugar–base
6. To which organelles does messenger RNA attach?
   a. chloroplasts c. mitochondria
   b. ribosomes d. lysosomes
7. The coded information in a DNA molecule directly determines the formation of
   a. polysaccharides. c. monosaccharides.
   b. lipids. d. polypeptides.
8. If the code for an amino acid is ATG on the DNA molecule, this code on the transfer RNA molecule may be written as
   a. ATG. c. AUG.
   b. CTG. d. CTA.

True or False

Determine whether each statement is true or false. If it is true, write "true." If it is false, change the underlined word or words to make the statement true.

1. A molecular group consisting of a sugar molecule, a phosphate group, and a nitrogenous base is a nucleic acid.
2. In a DNA molecule, a base pair would be composed of adenine and guanine.
3. Cytosine and adenine are purines.
4. During the replication of DNA, bonds are broken between the phosphate groups.
5. RNA contains the nitrogenous base uracil.
6. There are 20 different amino acids in a cell.
7. The coded message carried by messenger RNA is translated into polypeptides at organelles called chloroplasts.
8. The decoding of a messenger RNA message into a polypeptide chain is known as translation.

Word Relationships

A. *In each of the following sets of terms, three of the terms are related. One term does not belong. Determine the characteristic common to three of the terms and then identify the term that does not belong.*

1. deoxyribose, phosphate, DNA, uracil
2. amino acid, polypeptide, protein, translation
3. ribose, RNA, thymine, adenine
4. A—T, C—G, A—U, C—T

B. *Replace the underlined definition with the correct vocabulary word.*

5. The attraction between nitrogenous bases is the force that holds the two strands of DNA together.
6. Each combination of three nucleotides on messenger RNA specifies a specific amino acid that is to be placed in the polypeptide chain.
7. The RNA that carries amino acids to the ribosomes is a single strand of RNA that loops back on itself.
8. As a ribosome moves along a strand of messenger RNA, each codon is paired with its three nucleotides on transfer RNA that are complementary to the three nucleotides on messenger RNA.

CONCEPT MASTERY

Use your understanding of the concepts developed in the chapter to answer each of the following in a brief paragraph.

1. Describe Griffith's experiments involving bacterial transformation.
2. How did the study of bacteriophages lead scientists to support the idea that DNA carries hereditary material?
3. What was the contribution made by Hershey and Chase to understanding the genetic code?
4. How did Franklin's work contribute to the discovery of the structure of DNA?
5. Describe the contribution of Watson and Crick.
6. Describe DNA replication. What is its importance?
7. List three differences between DNA and RNA.
8. How is messenger RNA formed during transcription?
9. What is the function of the ribosomes?
10. What is the relationship between an amino acid and a codon?

CRITICAL AND CREATIVE THINKING

Discuss each of the following in a brief paragraph.

1. **Identifying patterns** Oxytocin is a hormone that helps to regulate blood pressure and stimulates the uterus to contract during childbirth. Following is a DNA sequence that could code for a part of a molecule of oxytocin: ACA ATA TAG CTT TTG ACG GGG AAC CCC ATT. Write the sequence of messenger RNA codons that would result from the transcription of this portion of DNA.
2. **Relating facts** How many guanines are in a DNA molecule 1000 base pairs long if 20% of the molecule consists of thymines?
3. **Applying concepts** Write out the messenger RNA sequence that would be transcribed from the following strand of DNA: T-A-C-A-A-G-T-A-C-T-T-G-T-T-T-C-T-T. Then using Figure 7-17 on page 149, write the amino acid sequence that would be translated when the messenger RNA combines with a ribosome.
4. **Using the writing process** Write a short story that follows a protein molecule from its point of origin in a corn kernel, through its use as cattle food, to a position of importance as a protein in your body.