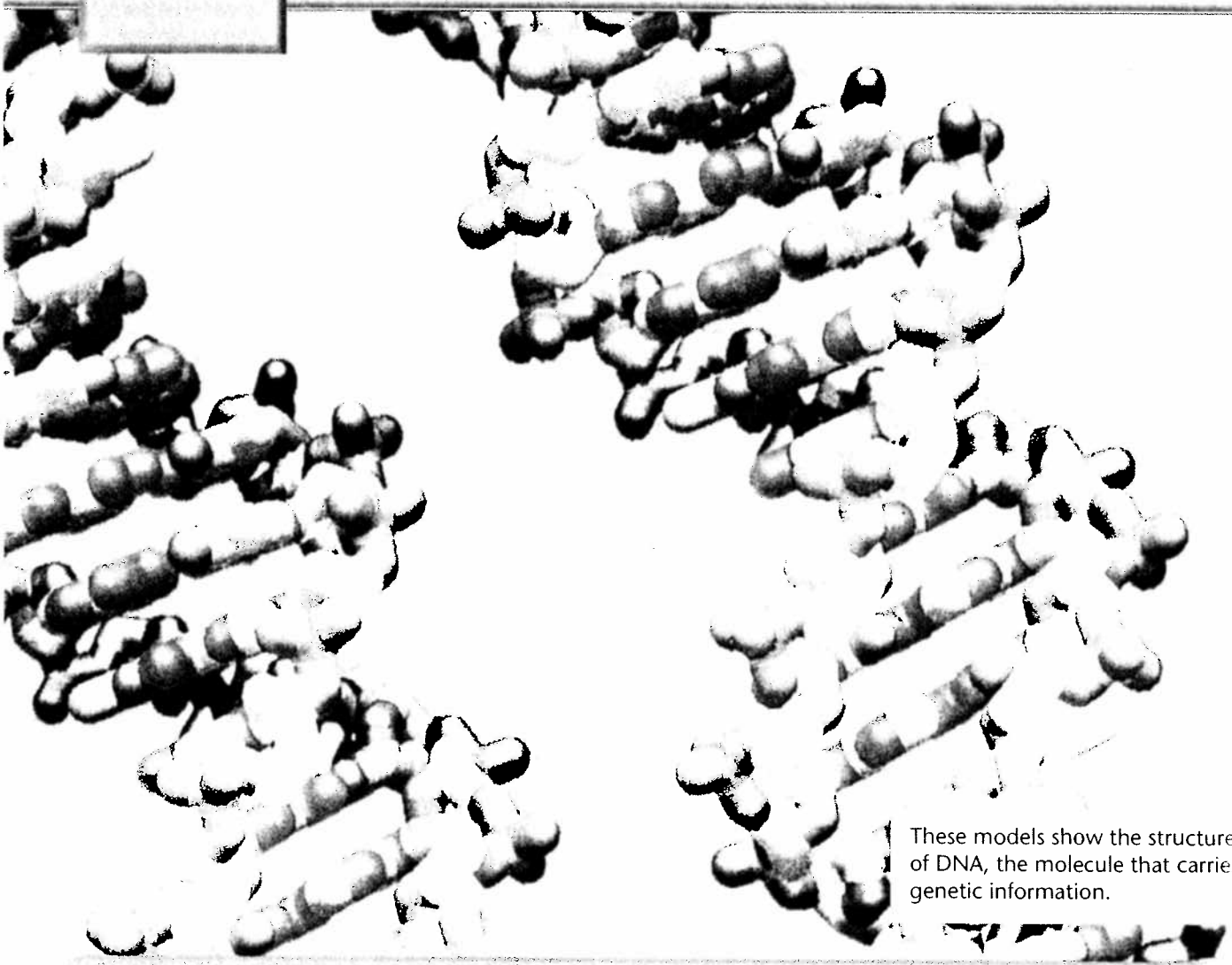
Ch 12

DNA and RNA



These models show the structure of DNA, the molecule that carries genetic information.

Inquiry Activity

1. Obtain 12 pop beads of four different colors.
2. Select a word that contains at least five different letters from the text on the next page. Use your beads to develop a code for your word.
3. Exchange your code and your coded bead chain with a classmate. Use the classmate's code to decipher his or her word.

1. How were you able to encode five different letters using only four colors?
2. How many different letters could you encode by using two beads to stand for each letter used in your message?
3. Could you encode the whole alphabet by using three beads for each letter?

12–1 DNA

7. 2.e. Students know DNA (deoxyribonucleic acid) is the genetic material of living organisms and is located in the chromosomes of each cell. 3f 6.a. Students know the general structures and functions of DNA, RNA, and protein. **BIIE 1.k. Recognize the cumulative nature of scientific evidence.**

How do genes work? What are they made of, and how do they determine the characteristics of organisms? Are genes single molecules, or are they longer structures made up of many molecules? In the middle of the 1900s, questions like these were on the minds of biologists everywhere.

To truly understand genetics, biologists first had to discover the chemical nature of the gene. If the structures that carry genetic information could be identified, it might be possible to understand how genes control the inherited characteristics of living things.

Griffith and Transformation

Like many stories in science, the discovery of the molecular nature of the gene began with an investigator who was actually looking for something else. In 1928, British scientist Frederick Griffith was trying to figure out how bacteria make people sick. More specifically, Griffith wanted to learn how certain types of bacteria produce a serious lung disease known as pneumonia.

Griffith had isolated two slightly different strains, or types, of pneumonia bacteria from mice. Both strains grew very well in culture plates in his lab, but only one of the strains caused pneumonia. 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.

Guide for Reading

Key Concepts

- What did scientists discover about the relationship between genes and DNA?
- What is the overall structure of the DNA molecule?

Vocabulary

transformation
bacteriophage
nucleotide
base pairing

Reading Strategy: Summarizing As you read, find the key ideas for the text under each blue heading. Write down a few key words from each main idea. Then, use the key words in your summary. Revise your summary, keeping only the most important ideas.

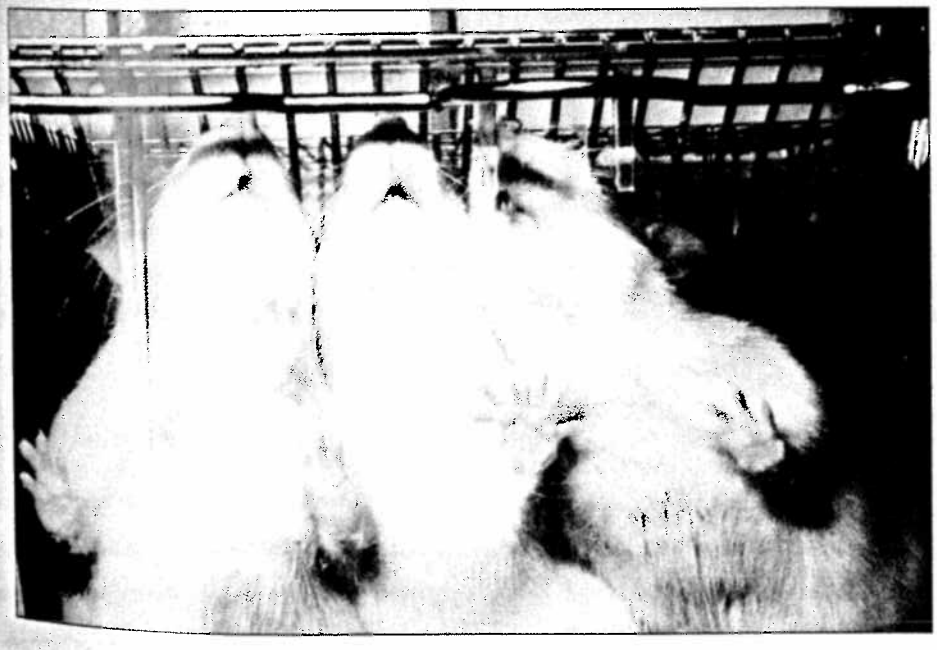
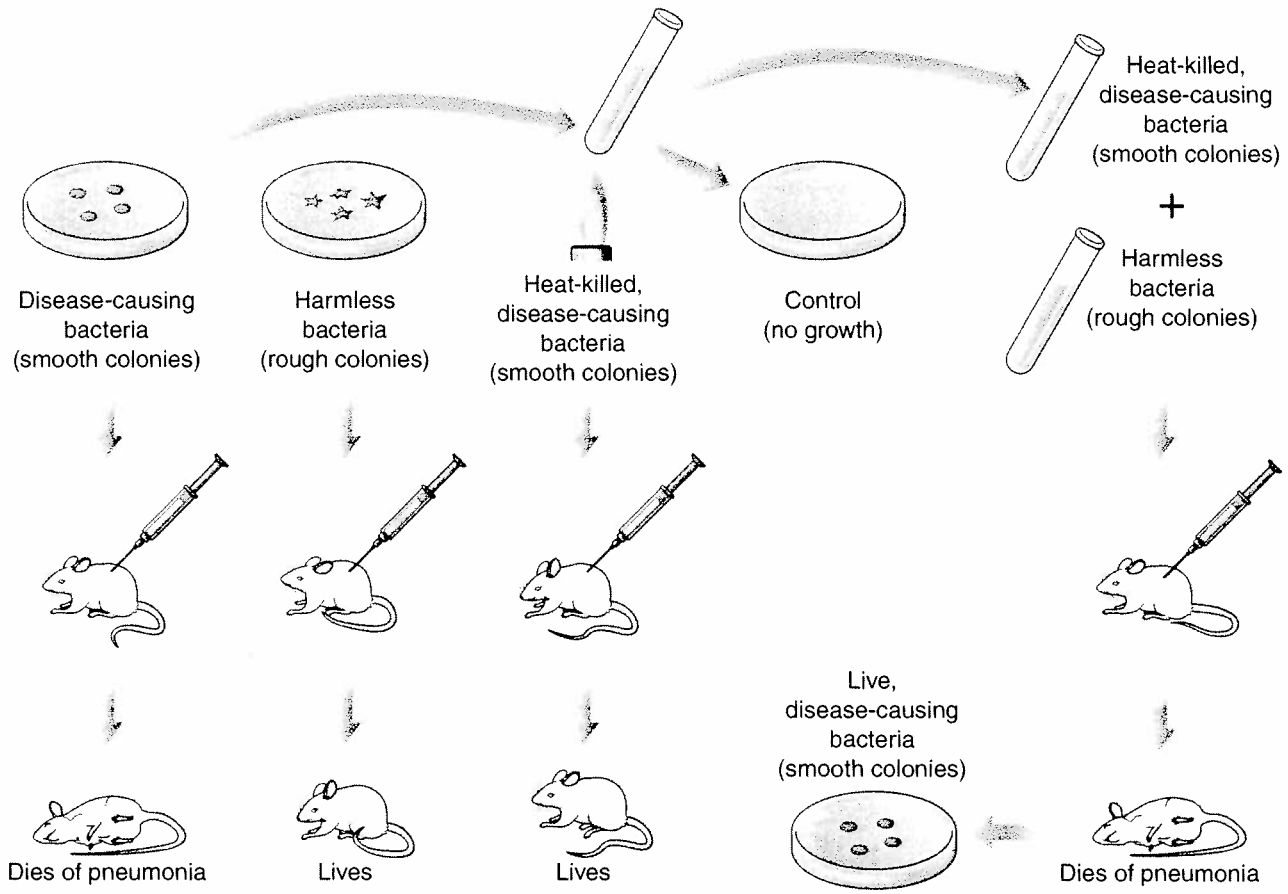


Figure 12–1 White mice like these are commonly used in scientific experiments.



▲ **Figure 12–2** Griffith injected mice with four different samples of bacteria. When injected separately, neither heat-killed, disease-causing bacteria nor live, harmless bacteria killed the mice. The two types injected together, however, caused fatal pneumonia. From this experiment, biologists inferred that genetic information could be transferred from one bacterium to another. **Inferring** ***After heating the disease-causing bacteria, why did Griffith test whether material from the bacterial culture would produce new colonies in a petri dish?***

Griffith's Experiments When Griffith injected mice with the disease-causing strain of bacteria, the mice developed pneumonia and died. When mice were injected with the harmless strain, they didn't get sick at all. Griffith wondered if the disease-causing bacteria might produce a poison.

To find out, he took a culture of these cells, heated the bacteria to kill them, and injected the heat-killed bacteria into mice. The mice survived, suggesting that the cause of pneumonia was not a chemical poison released by the disease-causing bacteria. Griffith's experiments are shown in **Figure 12–2.**

Transformation Griffith's next experiment produced an amazing result. He mixed his heat-killed, disease-causing bacteria with live, harmless ones and injected the mixture into mice. By themselves, neither should have made the mice sick. But to Griffith's amazement, the mice developed pneumonia and many died. When he examined the lungs of the mice, he found them filled not with the harmless bacteria, but with the disease-causing bacteria. Somehow the heat-killed bacteria had passed their disease-causing ability to the harmless strain. Griffith called this process **transformation** because one strain of bacteria (the harmless strain) had apparently been changed permanently into another (the disease-causing strain).

Griffith hypothesized that when the live, harmless bacteria and the heat-killed bacteria were mixed, some factor was transferred from the heat-killed cells into the live cells. That factor, he hypothesized, must contain information that could change harmless bacteria into disease-causing ones. Furthermore, since the ability to cause disease was inherited by the transformed bacteria's offspring, the transforming factor might be a gene.

Avery and DNA

In 1944, a group of scientists led by Canadian biologist Oswald Avery at the Rockefeller Institute in New York decided to repeat Griffith's work. They did so to determine which molecule in the heat-killed bacteria was most important for transformation. If transformation required just one particular molecule, that might well be the molecule of the gene.

Avery and his colleagues made an extract, or juice, from the heat-killed bacteria. They then carefully treated the extract with enzymes that destroyed proteins, lipids, carbohydrates, and other molecules, including the nucleic acid RNA. Transformation still occurred. Obviously, since these molecules had been destroyed, they were not responsible for the transformation.

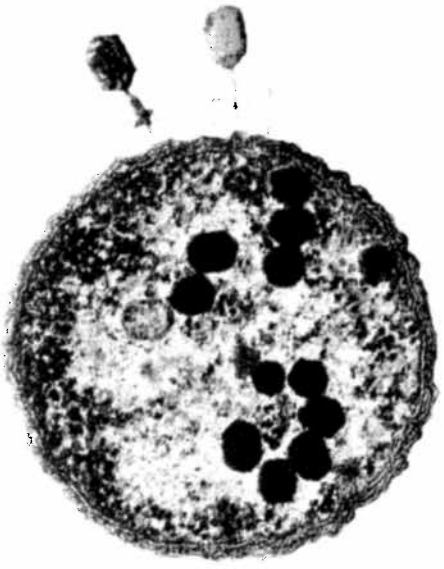
Avery and the other scientists repeated the experiment, this time using enzymes that would break down DNA. When they destroyed the nucleic acid DNA in the extract, transformation did not occur. There was just one possible conclusion. DNA was the transforming factor. **Avery and other scientists discovered that the nucleic acid DNA stores and transmits the genetic information from one generation of an organism to the next.**

The Hershey-Chase Experiment

Scientists are a skeptical group. It usually takes several experiments to convince them of something as important as the chemical nature of the gene. The most important of these experiments was performed in 1952 by two American scientists, Alfred Hershey and Martha Chase. They collaborated in studying viruses, nonliving particles smaller than a cell that can infect living organisms.

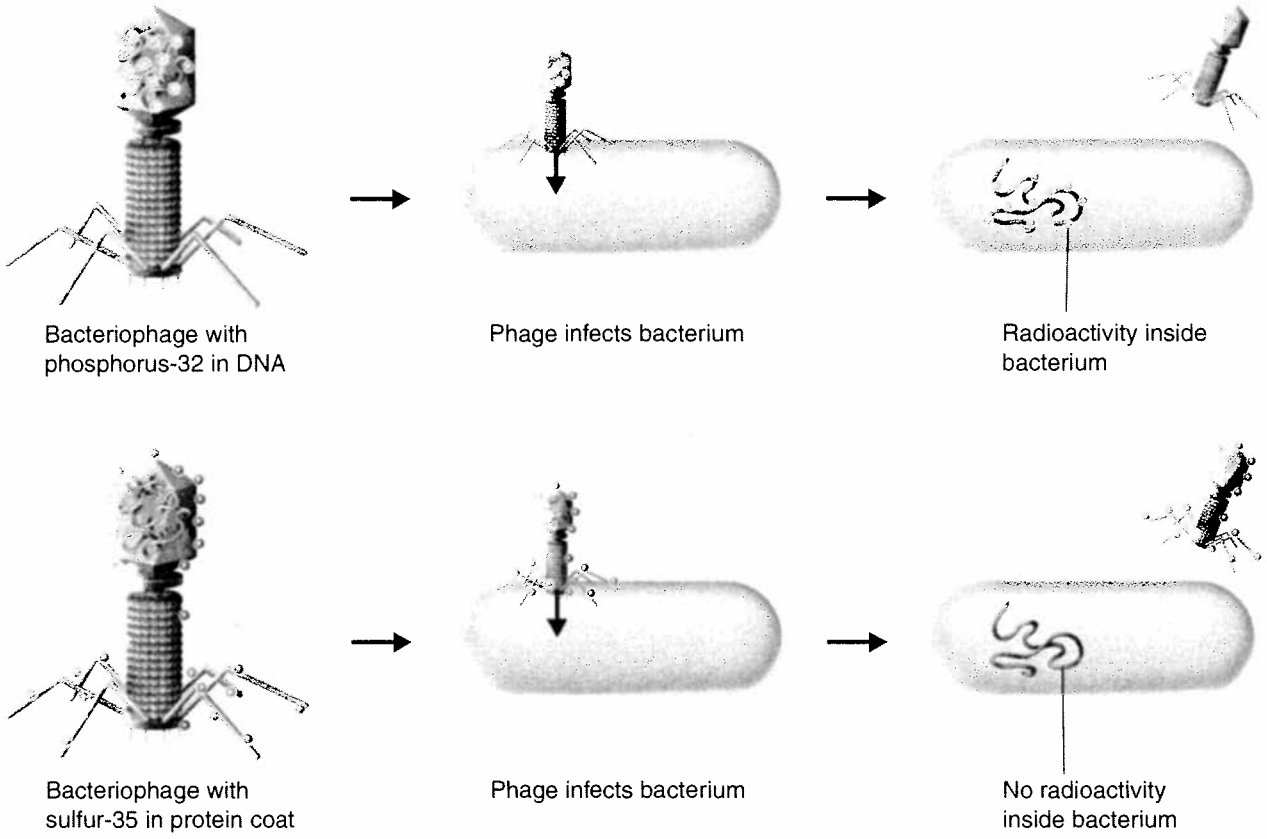
Bacteriophages One kind of virus that infects bacteria is known as a **bacteriophage** (bak-TEER-ee-uh-fayj), which means "bacteria eater." **Figure 12–3** shows typical bacteriophages. Bacteriophages are composed of a DNA or RNA core and a protein coat. When a bacteriophage enters a bacterium, the virus attaches to the surface of the cell and injects its genetic information into it. The viral genes act to produce many new bacteriophages, and they gradually destroy the bacterium. When the cell splits open, hundreds of new viruses burst out.

CHECKPOINT *What is a bacteriophage?*



(magnification: 25,000×)

▼ **Figure 12–3** A bacteriophage is a type of virus that infects and kills bacteria. This image shows two T2 bacteriophages (purple) invading an *E. coli* cell (green).
Comparing and Contrasting *How large are viruses compared with bacteria?*



▲ **Figure 12–4** Alfred Hershey and Martha Chase used different radioactive markers to label the DNA and proteins of bacteriophages. The bacteriophages injected only DNA into the bacteria, not proteins. **From these results, Hershey and Chase concluded that the genetic material of the bacteriophage was DNA.**

Radioactive Markers Hershey and Chase reasoned that if they could determine which part of the virus—the protein coat or the DNA core—entered the infected cell, they would learn whether genes were made of protein or DNA. To do this, they grew viruses in cultures containing radioactive isotopes of phosphorus-32 (^{32}P) and sulfur-35 (^{35}S). This was a clever strategy because proteins contain almost no phosphorus and DNA contains no sulfur. The radioactive substances could be used as markers. If ^{35}S was found in the bacteria, it would mean that the viruses' protein had been injected into the bacteria. If ^{32}P was found in the bacteria, then it was the DNA that had been injected.

The Hershey-Chase experiment is shown in **Figure 12–4.** The two scientists mixed the marked viruses with bacteria. Then, they waited a few minutes for the viruses to inject their genetic material. Next, they separated the viruses from the bacteria and tested the bacteria for radioactivity. Nearly all the radioactivity in the bacteria was from phosphorus (^{32}P), the marker found in DNA. **Hershey and Chase concluded that the genetic material of the bacteriophage was DNA, not protein.**

CHECKPOINT What part of the virus did the Hershey-Chase experiment show had entered the bacteria?

Components and Structure of DNA

You might think that knowing genes were made of DNA would have satisfied scientists, but that was not the case at all. Instead, they wondered how DNA, or any molecule for that matter, could do the three critical things that genes were known to do: First, genes had to carry information from one generation to the next; second, they had to put that information to work by determining the heritable characteristics of organisms; and third, genes had to be easily copied, because all of a cell's genetic information is replicated every time a cell divides. For DNA to do all of that, it would have to be a very special molecule indeed.

DNA is a long molecule made up of units called **nucleotides.** As **Figure 12–5** shows, each nucleotide is made up of three basic components: a 5-carbon sugar called deoxyribose, a phosphate group, and a nitrogenous (nitrogen-containing) base. There are four kinds of nitrogenous bases in DNA. Two of the nitrogenous bases, adenine (AD-uh-neen) and guanine (GWAH-neen), belong to a group of compounds known as purines. The remaining two bases, cytosine (SY-tuh-zeen) and thymine (THY-meen), are known as pyrimidines. Purines have two rings in their structures, whereas pyrimidines have one ring.

The backbone of a DNA chain is formed by sugar and phosphate groups of each nucleotide. The nitrogenous bases stick out sideways from the chain. The nucleotides can be joined together in any order, meaning that any sequence of bases is possible.

If you don't see much in **Figure 12–5** that could explain the remarkable properties of the gene, don't be surprised. In the 1940s and early 1950s, the leading biologists in the world thought of DNA as little more than a string of nucleotides. They were baffled, too. The four different nucleotides, like the 26 letters of the alphabet, could be strung together in many different ways, so it was possible they could carry coded genetic information. However, so could many other molecules, at least in principle. Was there something more to the structure of DNA?

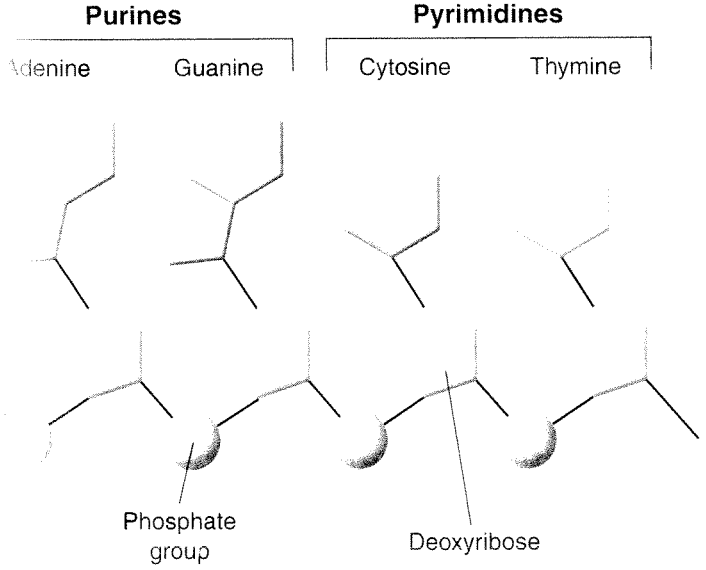
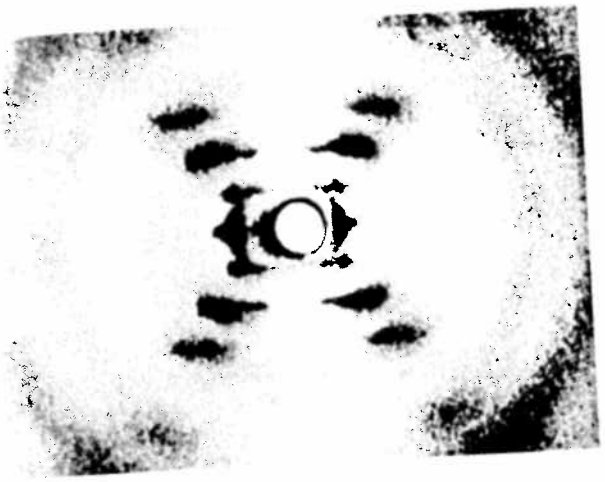


Figure 12–5 DNA is made up of nucleotides. Each nucleotide has three parts: a deoxyribose molecule, a phosphate group, and a nitrogenous base. There are four different bases in DNA: adenine, guanine, cytosine, and thymine.

How are the nucleotides joined together to form the DNA chain?



▲ **Figure 12–6** 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.

Chargaff's Rules One of the puzzling facts about DNA was a curious relationship between its nucleotides. Years earlier, Erwin Chargaff, an American biochemist, had discovered that the percentages of guanine [G] and cytosine [C] bases are almost equal in any sample of DNA. The same thing is true for the other two nucleotides, adenine [A] and thymine [T]. The observation that [A] = [T] and [G] = [C] became known as Chargaff's rules. Despite the fact that DNA samples from organisms as different as bacteria and humans obeyed this rule, neither Chargaff nor anyone else had the faintest idea why.

X-Ray Evidence In the early 1950s, a British scientist named Rosalind Franklin began to study DNA. She used a technique called X-ray diffraction to get information about the structure of the DNA molecule. Franklin 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 powerful X-ray beam at the concentrated DNA samples and recorded the scattering pattern of the X-rays on film. Franklin worked hard to make better and better patterns from DNA until the patterns became clear. The result of her work is the X-ray pattern shown in **Figure 12–6.**

BIIE 1.k

Biology and History

Discovering the Role of DNA

Genes and the laws of heredity were discovered before scientists identified the molecules that genes are made of. With the discovery of DNA, scientists have been able to explain how genes are replicated and how they function.

1928
Frederick Griffith
Griffith discovers that a factor in heat-killed, disease-causing bacteria can "transform" harmless bacteria into ones that can cause disease.

1944
Oswald Avery
Avery's team determines that genes are composed of DNA.

1951
Linus Pauling
Robert Corey
Pauling and Corey determine that the structure of a class of proteins is a helix.

1952
Rosalind Franklin
Franklin studies the DNA molecule using a technique called X-ray diffraction.

1900 1925 1950

By itself, Franklin's X-ray pattern does not reveal the structure of DNA, but it does carry some very important clues. The X-shaped pattern in the photograph in **Figure 12–6** shows that the strands in DNA are twisted around each other like the coils of a spring, a shape known as a helix. The angle of the *X* suggests that there are two strands in the structure. Other clues suggest that the nitrogenous bases are near the center of the molecule.

CHECKPOINT *What technique did Franklin use to study DNA?*

The Double Helix At the same time that Franklin was continuing her research, Francis Crick, a British physicist, and James Watson, an American biologist, were trying to understand the structure of DNA by building three-dimensional models of the molecule. Their models were made of cardboard and wire. They twisted and stretched the models in various ways, but their best efforts did nothing to explain DNA's properties.

Then, early in 1953, Watson was shown a copy of Franklin's remarkable X-ray pattern. The effect was immediate. In his book *The Double Helix,* Watson wrote: "The instant I saw the picture my mouth fell open and my pulse began to race." Using clues from Franklin's pattern, within weeks Watson and Crick had built a structural model that explained the puzzle of how DNA could carry information and how it could be copied. They published their results in a historic one-page paper in April of 1953.

Watson and Crick's model of DNA was a double helix, in which two strands were wound around each other.

Writing in Science

Do research in the library or on the Internet to find out what James Watson or Francis Crick has worked on since discovering the structure of DNA. Organize your findings about the scientist's work and write a short essay describing it.

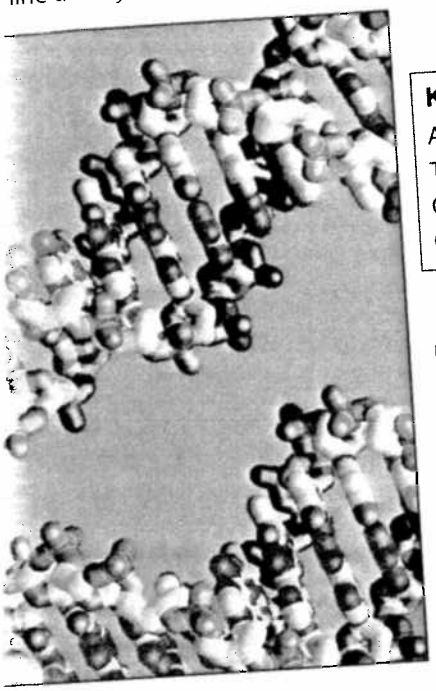
1953
James Watson
Francis Crick
Watson and Crick develop the double-helix model of the structure of DNA.

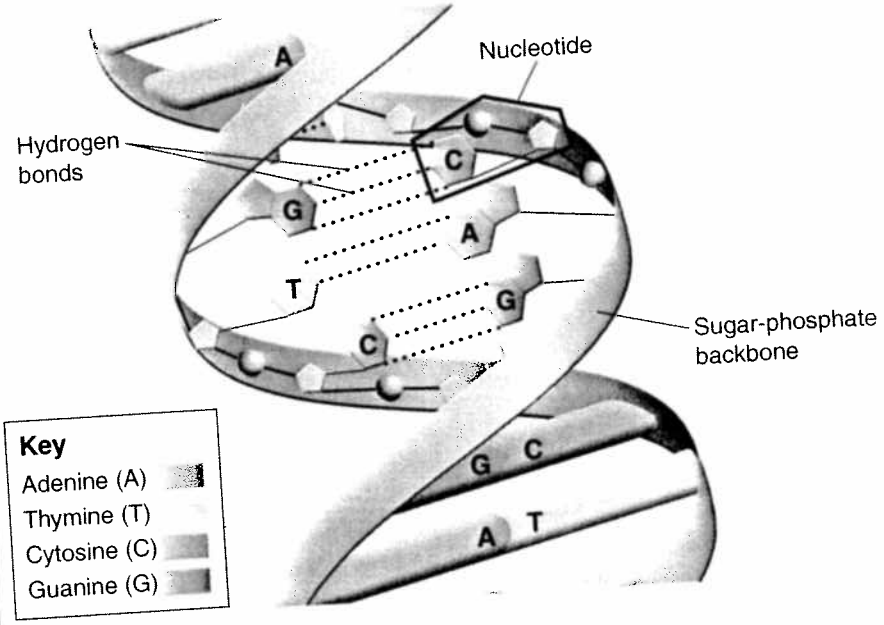
1960
Sydney Brenner
Brenner and other scientists show the existence of messenger RNA.

1977
Walter Gilbert
Gilbert, Allan Maxam, and Frederick Sanger develop methods to read the DNA sequence.

2000
Human Genome Project
The Human Genome Project—an attempt to sequence all human DNA—is essentially complete.

1950 1975 2000





Key
Adenine (A)
Thymine (T)
Cytosine (C)
Guanine (G)

re 12–7 DNA is a double in which two strands are nd around each other. Each d is made up of a chain of eotides. The two strands are held ther by hydrogen bonds between nine and thymine and between nine and cytosine.

A double helix looks like a twisted ladder or a spiral staircase. When Watson and Crick evaluated their DNA model, they realized that the double helix accounted for many of the features in Franklin's X-ray pattern but did not explain what forces held the two strands together. They then discovered that hydrogen bonds could form between certain nitrogenous bases and provide just enough force to hold the two strands together. As **Figure 12–7** shows, hydrogen bonds can form only between certain base pairs—adenine and thymine, and guanine and cytosine. Once they saw this, they realized that this principle, called **base pairing,** explained Chargaff's rules. Now there was a reason that [A] = [T] and [G] = [C]. For every adenine in a double-stranded DNA molecule, there had to be exactly one thymine molecule; for each cytosine molecule, there was one guanine molecule.

12–1 Section Assessment

1. **Key Concept** List the conclusions Griffith, Avery, Hershey, and Chase drew from their experiments.
2. **Key Concept** Describe Watson and Crick's model of the DNA molecule.
3. What are the four kinds of bases found in DNA?
4. Did Watson and Crick's model account for the equal amounts of thymine and adenine in DNA? Explain.
5. **Critical Thinking Inferring** Why did Hershey and Chase grow viruses in cultures that contained both radioactive phosphorus and radioactive sulfur? What might have happened if they had used only one radioactive substance?

Focus on the BIG Idea

Science as a Way of Knowing Using the experiments of Griffith, Avery, or Hershey and Chase as an example, develop a flowchart that shows how the scientist or scientists used scientific processes. Be sure to identify each process. *Hint*: You may wish to review Chapter 1, which describes scientific methods.

12.2 Chromosomes and DNA Replication

BI 5.b. Students know how to apply base-pairing rules to explain precise copying of DNA during semiconservative replication and transcription of information from DNA to mRNA.

DNA is present in such large amounts in many tissues that it's easy to extract and analyze. But where is DNA found in the cell? How is it organized? Where are the genes that Mendel first described a century and a half ago?

Guide for Reading

Key Concept
- What happens during DNA replication?

Vocabulary
chromatin
histone
replication
DNA polymerase

Reading Strategy: Asking Questions Before you read, study the diagram in **Figure 12–11.** Make a list of questions about the diagram. As you read, write down the answers to your questions.

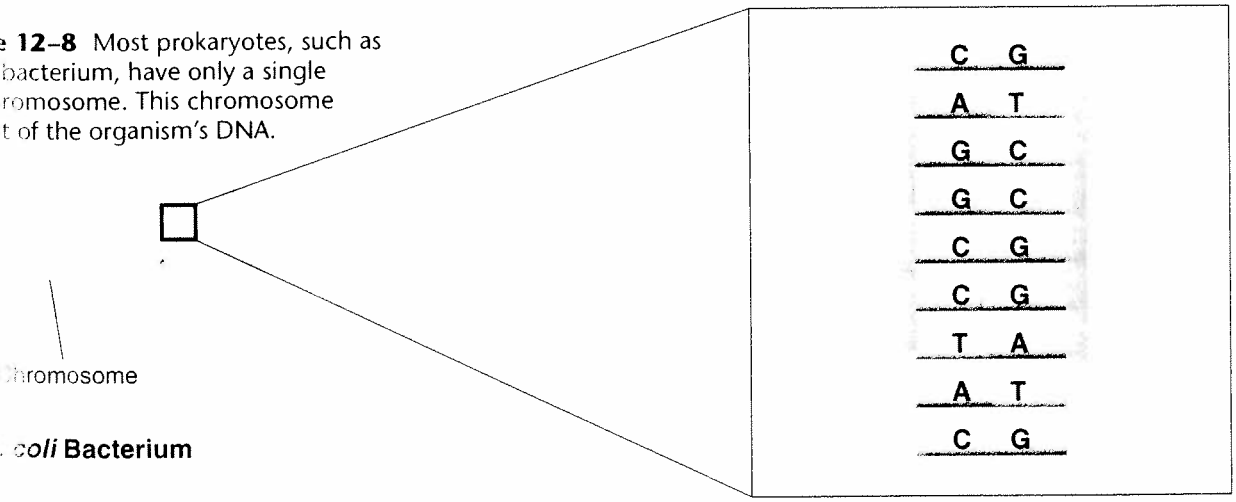
DNA and Chromosomes

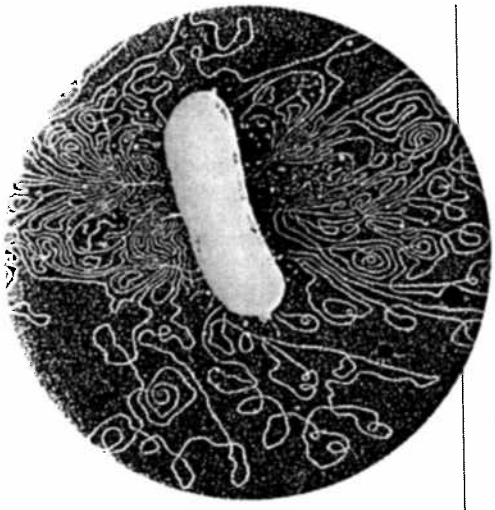
Prokaryotic cells lack nuclei and many of the organelles found in eukaryotes. Their DNA molecules are located in the cytoplasm. Most prokaryotes have a single circular DNA molecule that contains nearly all of the cell's genetic information. This large DNA molecule is usually referred to as the cell's chromosome, as shown in **Figure 12–8.**

Eukaryotic DNA is a bit more complicated. Many eukaryotes have as much as 1000 times the amount of DNA as prokaryotes. This DNA is not found free in the cytoplasm. Eukaryotic DNA is generally located in the cell nucleus in the form of a number of chromosomes. The number of chromosomes varies widely from one species to the next. For example, diploid human cells have 46 chromosomes, *Drosophila* cells have 8, and giant sequoia tree cells have 22.

DNA Length DNA molecules are surprisingly long. The chromosome of the prokaryote *E. coli,* which can live in the human colon (large intestine), contains 4,639,221 base pairs. The length of such a DNA molecule is roughly 1.6 mm, which doesn't sound like much until you think about the small size of a bacterium. To fit inside a typical bacterium, the DNA molecule must be folded into a space only one one-thousandth of its length.

Figure 12–8 Most prokaryotes, such as this *E. coli* bacterium, have only a single circular chromosome. This chromosome holds most of the organism's DNA.





▲ **Figure 12–9** The DNA in a bacterium is about 1000 times as long as the bacterium itself. It must therefore be very tightly folded. **Using Analogies** *Compare DNA in a bacterium to a rope jammed into a backpack.*

To get a rough idea of what this means, think of a large school backpack. Then, imagine trying to pack a 300-meter length of rope into the backpack! **Figure 12–9,** which shows DNA spilling out from a ruptured bacterium, indicates how dramatically the DNA must be folded to fit within the cell.

Chromosome Structure The DNA in eukaryotic cells is packed even more tightly. A human cell contains almost 1000 times as many base pairs of DNA as a bacterium. The nucleus of a human cell contains more than 1 meter of DNA. How is so much DNA folded into tiny chromosomes? The answer can be found in the composition of eukaryotic chromosomes.

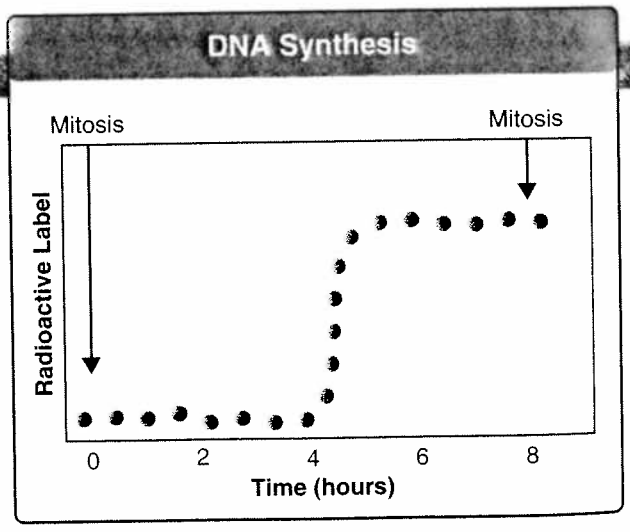
Eukaryotic chromosomes contain both DNA and protein, tightly packed together to form a substance called **chromatin.** Chromatin consists of DNA that is tightly coiled around proteins called **histones,** as shown in **Figure 12–10.** Together, the DNA and histone molecules form a beadlike structure called a nucleosome. Nucleosomes pack with one another to form a thick fiber, which is shortened by a system of loops and coils.

During most of the cell cycle, these fibers are dispersed in the nucleus so that individual chromosomes are not visible. During mitosis, however, the fibers of each individual chromosome are drawn together, forming the tightly packed chromosomes you can see through a light microscope in dividing cells. The tight packing of nucleosomes may help separate chromosomes during mitosis. There is also some evidence that changes in chromatin structure and histone-DNA binding are associated with changes in gene activity and expression.

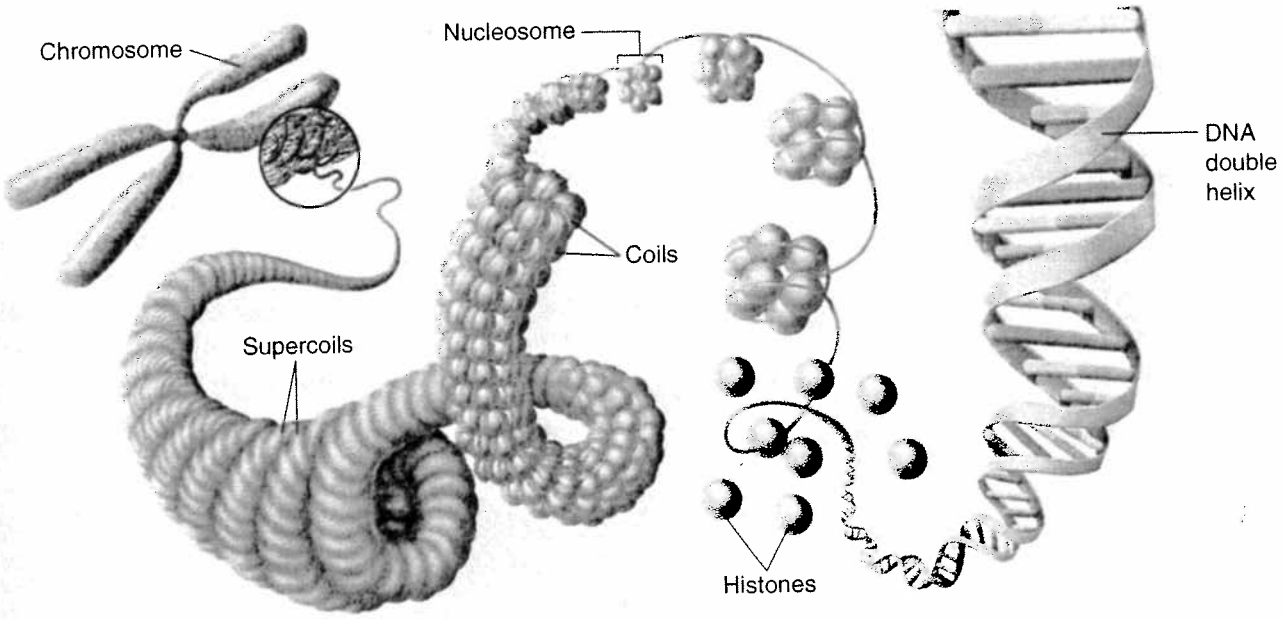
Analyzing Data

Synthesis of New DNA Molecules

How can you investigate when and where cells synthesize DNA? Scientists have done this by briefly adding radioactively labeled thymine to the medium in which a cell grows. A cell that is synthesizing DNA will take the labeled thymine nucleotide into its DNA. The graph shows the total amount of radioactive label taken into DNA from thymine during an eight-hour period between two cell divisions.



1. **Interpreting Graphics** Contrast the amounts of radioactivity incorporated during the following times: (a) the first four hours of the experiment, (b) the next two hours, and (c) the final two hours.
2. **Drawing Conclusions** Is DNA synthesized continually during the cell cycle (the period between cell divisions)? If not, during what phase is it synthesized? How long is that phase?
3. **Predicting** Which organelle or cell structure would you expect to contain the most radioactivity after this experiment? Explain.



▲ **Figure 12–10** Eukaryotic chromosomes contain DNA wrapped around proteins called histones. The strands of nucleosomes are tightly coiled and supercoiled to form chromosomes. **Interpreting Graphics** *What is each DNA-histone complex called?*

What do nucleosomes do? Nucleosomes seem to be able to fold enormous lengths of DNA into the tiny space available in the cell nucleus. This is such an important function that the histone proteins themselves have changed very little during evolution—probably because mistakes in DNA folding could harm a cell's ability to reproduce.

CHECKPOINT *What is chromatin?*

DNA Replication

When Watson and Crick discovered the double helix structure of DNA, there was one more remarkable aspect that they recognized immediately. The structure explained how DNA could be copied, or replicated. Each strand of the DNA double helix has all the information needed to reconstruct the other half by the mechanism of base pairing. Because each strand can be used to make the other strand, the strands are said to be complementary. If you could separate the two strands, the rules of base pairing would allow you to reconstruct the base sequence of the other strand.

In most prokaryotes, DNA replication begins at a single point in the chromosome and proceeds, often in two directions, until the entire chromosome is replicated. In the larger eukaryotic chromosomes, DNA replication occurs at hundreds of places. Replication proceeds in both directions until each chromosome is completely copied. The sites where separation and replication occur are called replication forks.

DNA Replication

Figure 12–11 **During DNA replication, the DNA molecule produces two new complementary strands. Each strand of the double helix of DNA serves as a template for the new strand.** The electron micrograph shows a double strand of human DNA.

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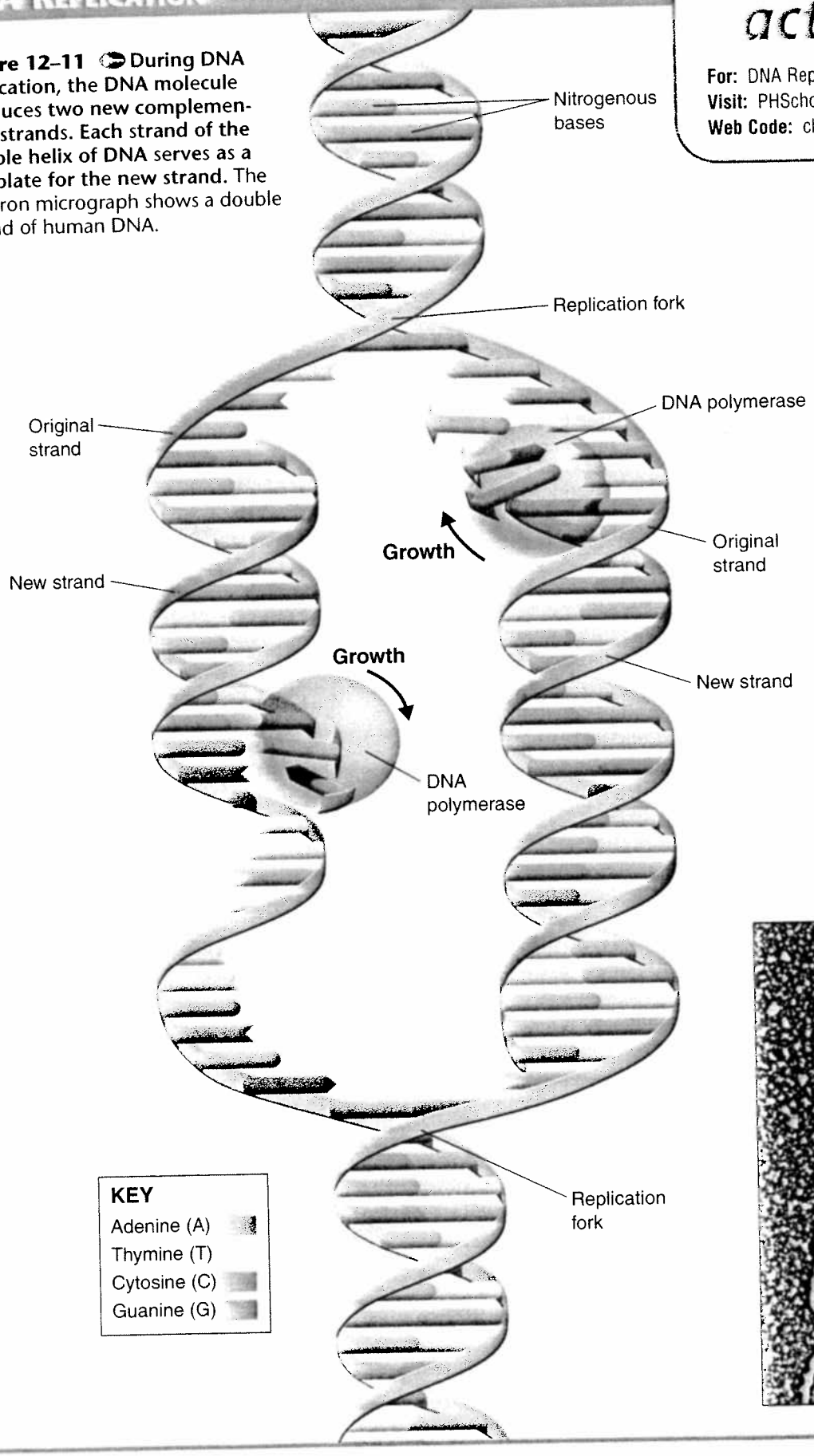
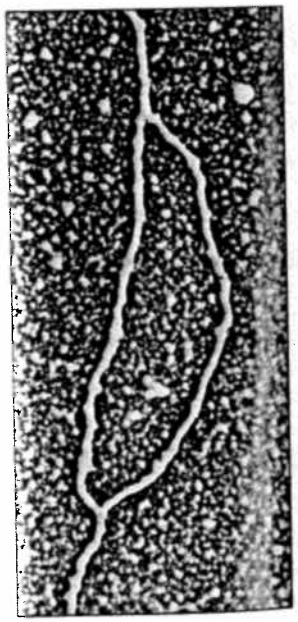




Duplicating DNA Before a cell divides, it duplicates its DNA in a copying process called **replication.** This process ensures that each resulting cell will have a complete set of DNA molecules. **During DNA replication, the DNA molecule separates into two strands, and then produces two new complementary strands following the rules of base pairing. Each strand of the double helix of DNA serves as a template, or model, for the new strand.**

Figure 12–11 shows the process of DNA replication. The two strands of the double helix have separated, allowing two replication forks to form. As each new strand forms, new bases are added following the rules of base pairing. In other words, if the base on the old strand is adenine, thymine is added to the newly forming strand. Likewise, guanine is always paired to cytosine.

For example, a strand that has the bases TACGTT produces a strand with the complementary bases ATGCAA. The result is two DNA molecules identical to each other and to the original molecule. Note that each DNA molecule resulting from replication has one original strand and one new strand.

How Replication Occurs DNA replication is carried out by a series of enzymes. These enzymes "unzip" a molecule of DNA. The unzipping occurs when the hydrogen bonds between the base pairs are broken and the two strands of the molecule unwind. Each strand serves as a template for the attachment of complementary bases.

DNA replication involves a host of enzymes and regulatory molecules. You may recall that enzymes are highly specific. For this reason, they are often named for the reactions they catalyze. The principal enzyme involved in DNA replication is called **DNA polymerase** (PAHL-ih-mur-ayz) because it joins individual nucleotides to produce a DNA molecule, which is, of course, a polymer. DNA polymerase also "proofreads" each new DNA strand, helping to maximize the odds that each molecule is a perfect copy of the original DNA.

12.1 Section Assessment

1. **Concept** Explain how DNA is replicated.
2. Where and in what form is eukaryotic DNA found?
3. How are the long DNA molecules found in eukaryotes packed into short chromosomes?
4. How are histones related to nucleosomes?
5. What is the role of DNA polymerase in DNA replication?
6. **Critical Thinking** How is the structure of chromosomes in eukaryotes different from the structure of chromosomes in prokaryotes?

Thinking Visually

Creating a Venn Diagram
Make a Venn diagram that compares the process of DNA replication in prokaryotes and eukaryotes. Compare the location, steps, and end products of the process in each kind of cell. (For more on Venn diagrams, see Appendix A.)

12–3 RNA and Protein Synthesis

BI 1.d. Students know the central dogma of molecular biology outlines the flow of information from transcription of ribonucleic acid (RNA) in the nucleus to translation of proteins on ribosomes in the cytoplasm. **BI 4.a.** Students know the general pathway by which ribosomes synthesize proteins, using tRNAs to translate genetic information in mRNA. **BI 4.b.** Students know how to apply the genetic coding rules to predict the sequence of amino acids from a sequence of codons in RNA. **BI 5.a.** Students know the general structures and functions of DNA, RNA, and protein.

Guide for Reading

Key Concepts

- What are the three main types of RNA?
- What is transcription?
- What is translation?

Vocabulary

gene
messenger RNA
ribosomal RNA
transfer RNA
transcription
RNA polymerase
promoter
intron
exon
codon
translation
anticodon

Reading Strategy: Using Visuals Before you read, preview **Figure 12–18.** As you read, notice what happens in each step of translation, or protein synthesis.

The double helix structure explains how DNA can be copied, but it does not explain how a gene works. In molecular terms, **genes** are coded DNA instructions that control the production of proteins within the cell. The first step in decoding these genetic messages is to copy part of the nucleotide sequence from DNA into RNA, or ribonucleic acid. These RNA molecules contain coded information for making proteins.

The Structure of RNA

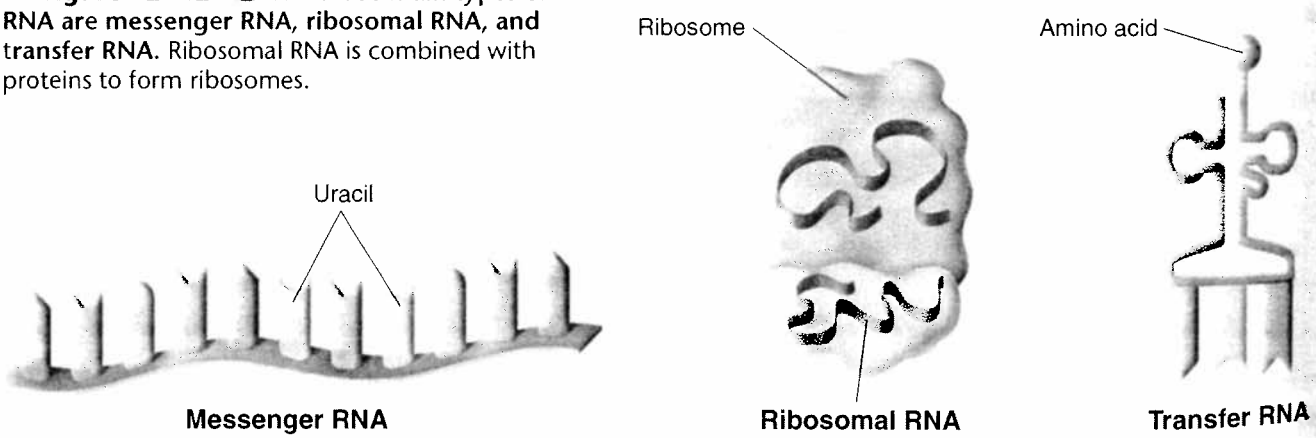
RNA, like DNA, consists of a long chain of nucleotides. As you may recall, each nucleotide is made up of a 5-carbon sugar, a phosphate group, and a nitrogenous base. There are three main differences between RNA and DNA: The sugar in RNA is ribose instead of deoxyribose, RNA is generally single-stranded, and RNA contains uracil in place of thymine.

You can think of an RNA molecule as a disposable copy of a segment of DNA. In many cases, an RNA molecule is a working copy of a single gene. The ability to copy a single DNA sequence into RNA makes it possible for a single gene to produce hundreds or even thousands of RNA molecules.

Types of RNA

RNA molecules have many functions, but in the majority of cells most RNA molecules are involved in just one job—protein synthesis. The assembly of amino acids into proteins is controlled by RNA. **There are three main types of RNA: messenger RNA, ribosomal RNA, and transfer RNA.** The structures of these molecules are shown in **Figure 12–12.**

Figure 12–12 **The three main types of RNA are messenger RNA, ribosomal RNA, and transfer RNA.** Ribosomal RNA is combined with proteins to form ribosomes.



Most genes contain instructions for assembling amino acids into proteins. The RNA molecules that carry copies of these instructions are known as **messenger RNA** (mRNA) because they serve as "messengers" from DNA to the rest of the cell.

Proteins are assembled on ribosomes, shown in **Figure 12–13.** Ribosomes are made up of several dozen proteins, as well as a form of RNA known as **ribosomal RNA** (rRNA).

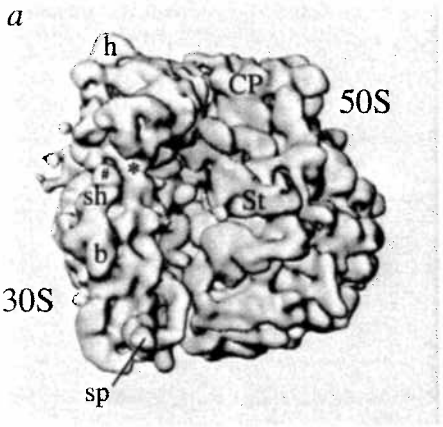
During the construction of a protein, a third type of RNA molecule transfers each amino acid to the ribosome as it is specified by coded messages in mRNA. These RNA molecules are known as **transfer RNA** (tRNA).

CHECKPOINT *What are ribosomes made of?*

Transcription

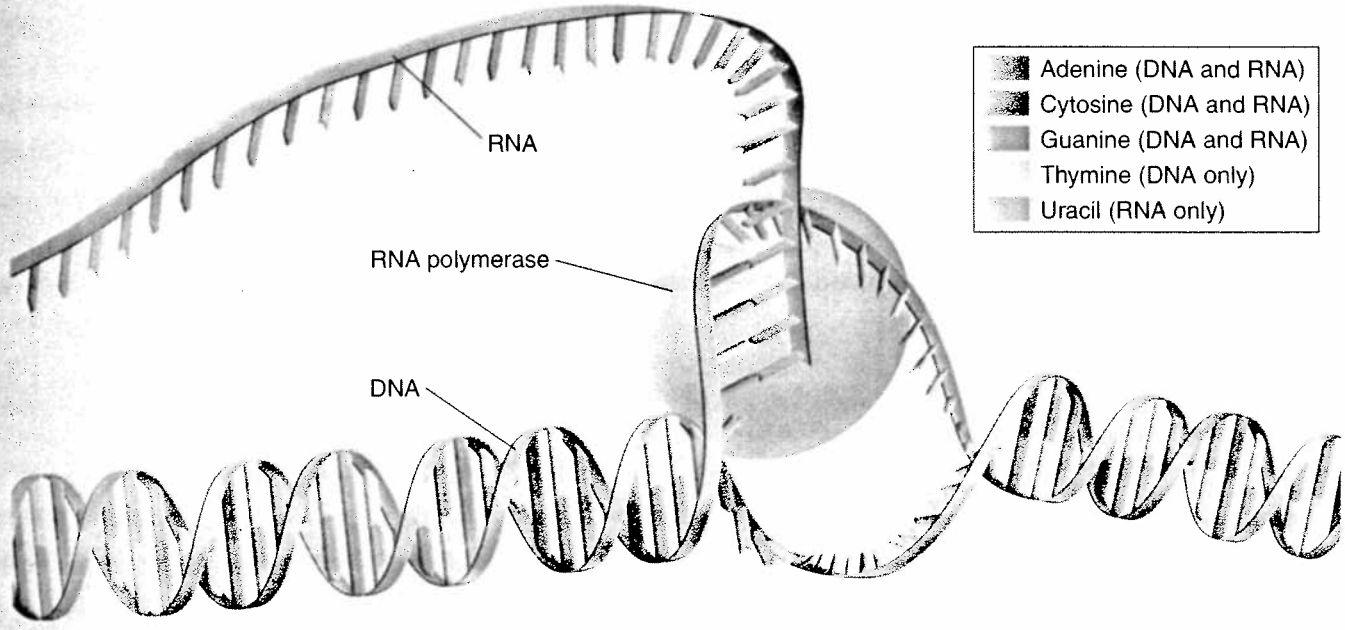
RNA molecules are produced by copying part of the nucleotide sequence of DNA into a complementary sequence in RNA, a process called **transcription.** Transcription requires an enzyme known as **RNA polymerase** that is similar to DNA polymerase. **During transcription, RNA polymerase binds to DNA and separates the DNA strands. RNA polymerase then uses one strand of DNA as a template from which nucleotides are assembled into a strand of RNA.** The process of transcription is shown in **Figure 12–14.**

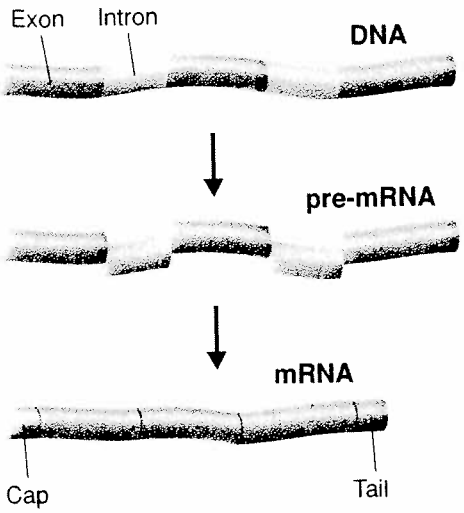
How does RNA polymerase "know" where to start and stop making an RNA copy of DNA? The answer to this question begins with the observation that RNA polymerase doesn't bind to DNA just anywhere. The enzyme will bind only to regions of DNA known as **promoters,** which have specific base sequences. In effect, promoters are signals in DNA that indicate to the enzyme where to bind to make RNA. Similar signals in DNA cause transcription to stop when the new RNA molecule is completed.



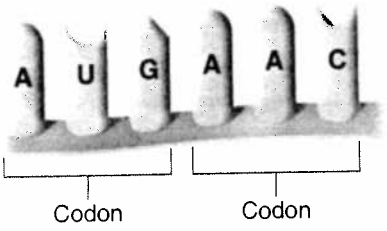
▲ **Figure 12–13** In this detailed model of a ribosome, the two subunits of the ribosome are shown in yellow and blue. The model was produced using cryo-electron microscopy. Data from more than 73,000 electron micrographs, taken at ultra-cold temperatures to preserve ribosome structure, were analyzed to produce the model.

▼ **Figure 12–14** During transcription, RNA polymerase uses one strand of DNA as a template to assemble nucleotides into a strand of RNA.





▲ **Figure 12–15** Many RNA molecules have sections, called introns, edited out of them before they become functional. The remaining pieces, called exons, are spliced together. Then, a cap and tail are added to form the final RNA molecule. **Predicting** *What do you think would happen if the introns were not removed from the pre-mRNA?*



▲ **Figure 12–16** A codon is a group of three nucleotides on messenger RNA that specify a particular amino acid. **Observing** *What are the three-letter groups of the two codons shown here?*

RNA Editing

Like a writer's first draft, many RNA molecules require a bit of editing before they are ready to go into action. Remember that an RNA molecule is produced by copying DNA. Surprisingly, the DNA of eukaryotic genes contains sequences of nucleotides, called **introns,** that are not involved in coding for proteins. The DNA sequences that code for proteins are called **exons** because they are "expressed" in the synthesis of proteins. When RNA molecules are formed, both the introns and the exons are copied from the DNA. However, the introns are cut out of RNA molecules while they are still in the nucleus. The remaining exons are then spliced back together to form the final mRNA as shown in **Figure 12–15.**

Why do cells use energy to make a large RNA molecule and then throw parts of it away? That's a good question, and biologists still do not have a complete answer to it. Some RNA molecules may be cut and spliced in different ways in different tissues, making it possible for a single gene to produce several different forms of RNA. Introns and exons may also play a role in evolution. This would make it possible for very small changes in DNA sequences to have dramatic effects in gene expression.

CHECKPOINT *What are introns and exons?*

The Genetic Code

Proteins are made by joining amino acids into long chains called polypeptides. Each polypeptide contains a combination of any or all of the 20 different amino acids. The properties of proteins are determined by the order in which different amino acids are joined together to produce polypeptides. How, you might wonder, can a particular order of nitrogenous bases in DNA and RNA molecules be translated into a particular order of amino acids in a polypeptide?

The "language" of mRNA instructions is called the genetic code. As you know, RNA contains four different bases: A, U, C, and G. In effect, the code is written in a language that has only four "letters." How can a code with just four letters carry instructions for 20 different amino acids? The genetic code is read three letters at a time, so that each "word" of the coded message is three bases long. Each three-letter "word" in mRNA is known as a codon, as shown in **Figure 12–16.** A **codon** consists of three consecutive nucleotides that specify a single amino acid that is to be added to the polypeptide. For example, consider the following RNA sequence:

UCGCACGGU

This sequence would be read three bases at a time as:

UCG-CAC-GGU

The codons represent the different amino acids:

UCG-CAC-GGU

Serine-Histidine-Glycine

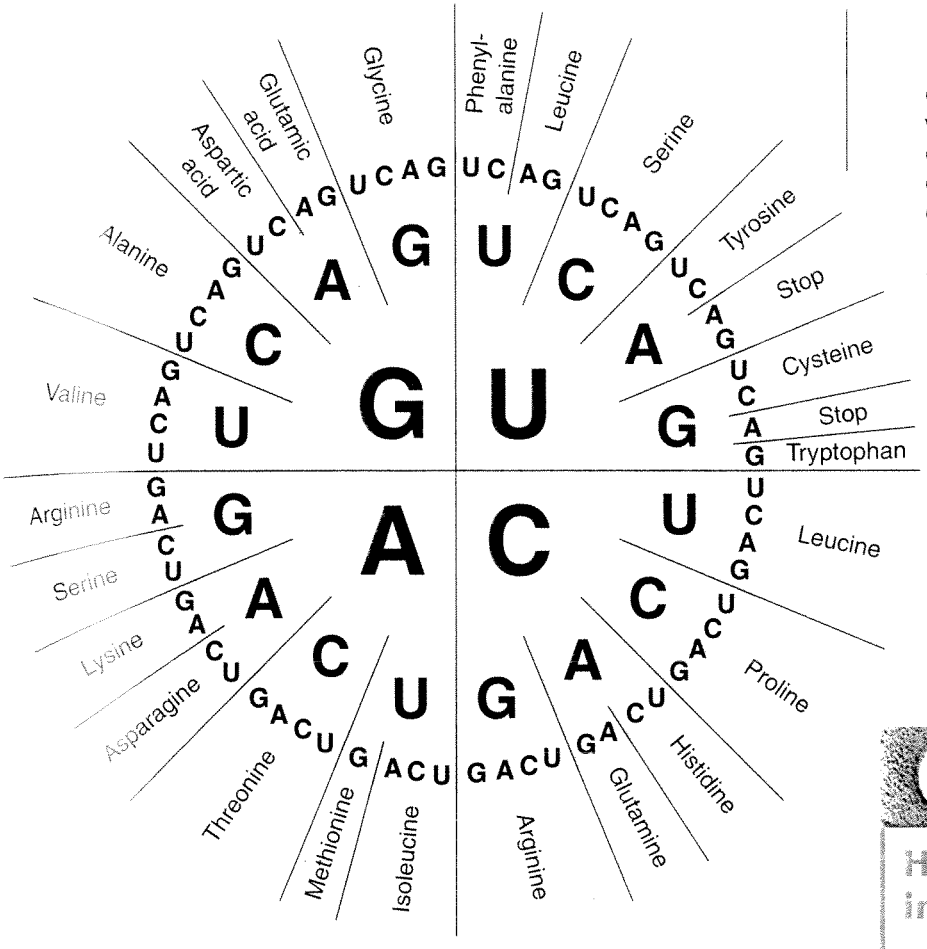


Figure 12–17 The genetic code shows the amino acid to which each of the 64 possible codons corresponds. To decode a codon, start at the middle of the circle and move outward. *Interpreting Graphics* ***For what amino acid does the codon UGC code?***

Because there are four different bases, there are 64 possible three-base codons ($4 \times 4 \times 4 = 64$). **Figure 12–17** shows all 64 possible codons of the genetic code. As you can see, some amino acids can be specified by more than one codon. For example, six different codons specify the amino acid leucine, and six others specify arginine.

There is also one codon, AUG, that can either specify methionine or serve as the initiation, or "start," codon for protein synthesis. Notice also that there are three "stop" codons that do not code for any amino acid. Stop codons act like the period at the end of a sentence; they signify the end of a polypeptide, which consists of many amino acids.

Translation

The sequence of nucleotide bases in an mRNA molecule serves as instructions for the order in which amino acids should be joined together to produce a polypeptide. However, anyone who has tried to assemble a complex toy knows that instructions generally don't do the job themselves. They need something to read them and put them to use. In the cell, that "something" is a tiny factory called the ribosome.

Quick Lab

How does a cell interpret DNA?

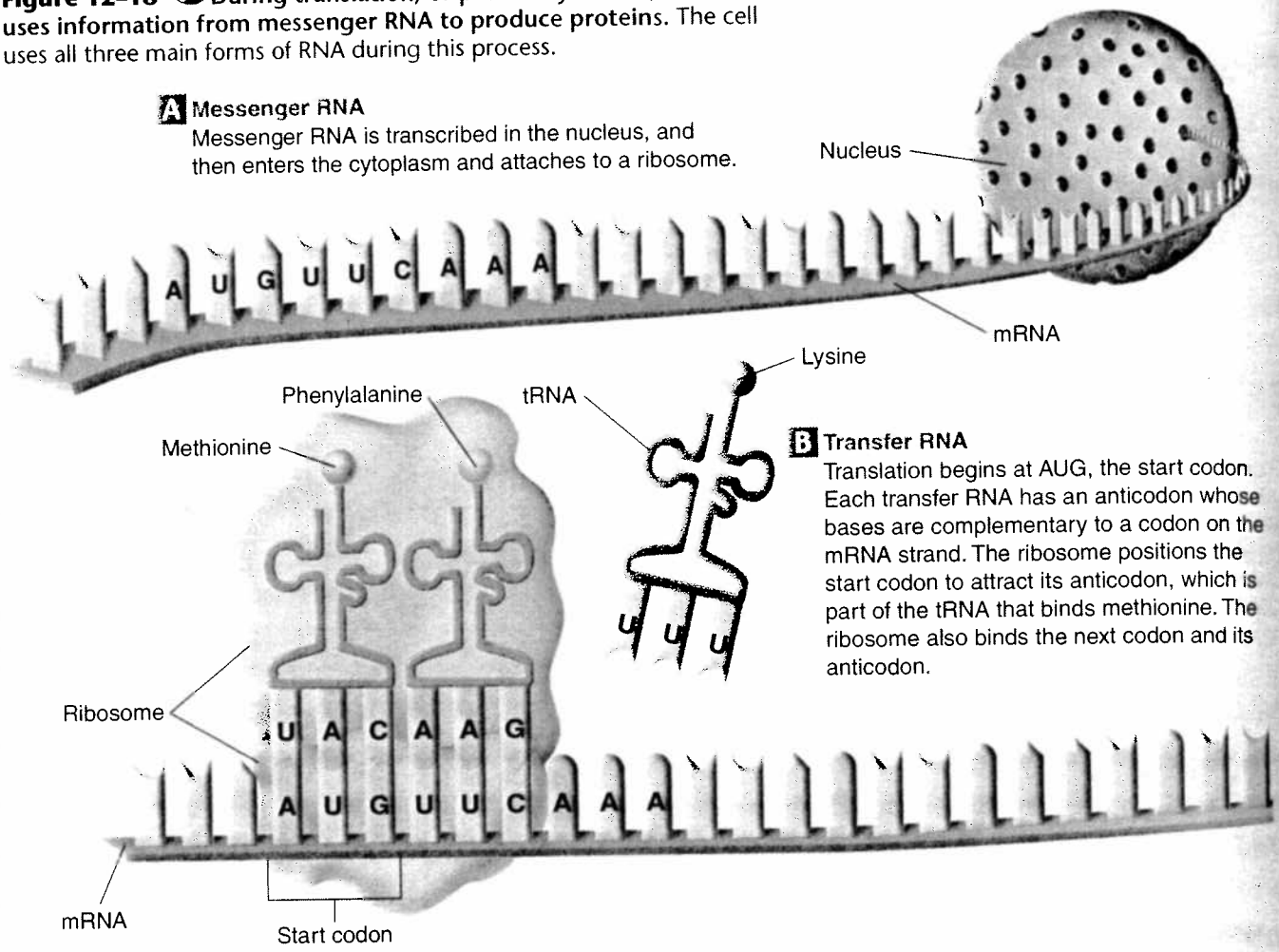
Procedure **BI 4.b**

1. A certain gene has the following sequence of nucleotides:
   GACAAGTCCACAATC
   Write this sequence on a sheet of paper.
2. From left to right, write the sequence of the mRNA molecule transcribed from this gene.
3. Look at **Figure 12–17.** Reading the mRNA codons from left to right, write the amino acid sequence of the polypeptide translated from the mRNA.
4. Repeat step 3, reading the codons from right to left.

Analyze and Conclude

1. *Applying Concepts* Why did steps 3 and 4 produce different polypeptides?
2. *Inferring* Do cells usually decode nucleotides in one direction only or in either direction?

Figure 12–18 **During translation, or protein synthesis, the cell uses information from messenger RNA to produce proteins.** The cell uses all three main forms of RNA during this process.

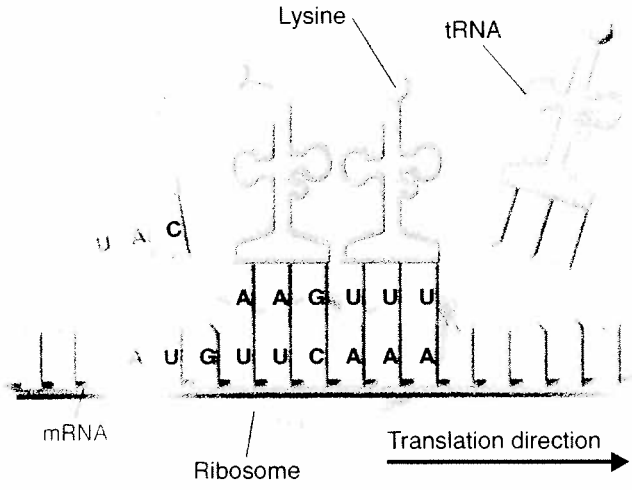


The decoding of an mRNA message into a polypeptide chain (protein) is known as **translation.** Translation takes place on ribosomes. **During translation, the cell uses information from messenger RNA to produce proteins.** Refer to **Figure 12–18** as you read about translation.

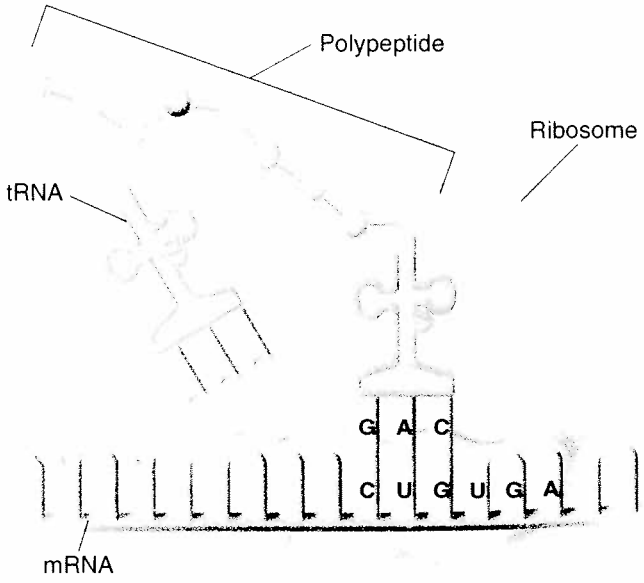
A Before translation occurs, messenger RNA is transcribed from DNA in the nucleus and released into the cytoplasm.

B Translation begins when an mRNA molecule in the cytoplasm attaches to a ribosome. As each codon of the mRNA molecule moves through the ribosome, the proper amino acid is brought into the ribosome by tRNA. In the ribosome, the amino acid is transferred to the growing polypeptide chain.

Each tRNA molecule carries only one kind of amino acid. For example, some tRNA molecules carry methionine, others carry arginine, and still others carry serine. In addition to an amino acid, each tRNA molecule has three unpaired bases. These bases, called the **anticodon,** are complementary to one mRNA codon.



The ribosome joins the two amino acids—methionine and phenylalanine—and breaks the bond between methionine and its tRNA. The tRNA floats away from the ribosome, allowing the ribosome to bind another tRNA. The ribosome moves along the mRNA, binding new tRNA molecules and amino acids.



D The process continues until the ribosome reaches one of the three stop codons. The result is a complete polypeptide.

In the case of the tRNA molecule for methionine, the anticodon bases are UAC, which pair with the methionine codon, AUG. The ribosome has a second binding site for a tRNA molecule for the next codon. If that next codon is UUC, a tRNA molecule with an AAG anticodon would fit against the mRNA molecule held in the ribosome. That second tRNA molecule would bring the amino acid phenylalanine into the ribosome.

C Like an assembly line worker who attaches one part to another, the ribosome forms a peptide bond between the first and second amino acids, methionine and phenylalanine. At the same time, the ribosome breaks the bond that had held the first tRNA molecule to its amino acid and releases the tRNA molecule. The ribosome then moves to the third codon, where a tRNA molecule brings it the amino acid specified by the third codon.

D The polypeptide chain continues to grow until the ribosome reaches a stop codon on the mRNA molecule. When the ribosome reaches a stop codon, it releases the newly formed polypeptide and the mRNA molecule, completing the process of translation.

Go Online

For: Protein Synthesis activity
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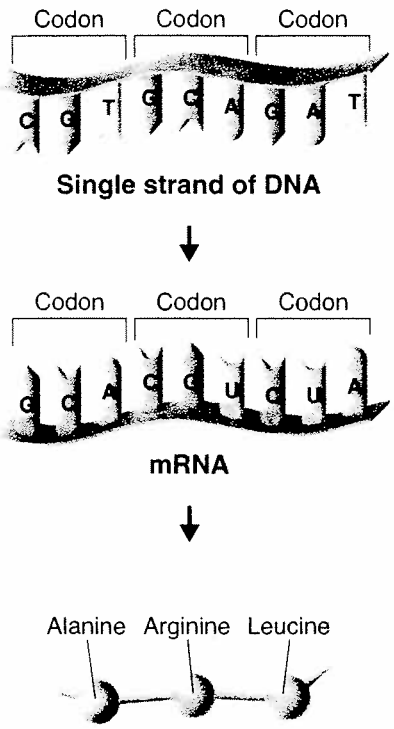


▲ **Figure 12–19** This diagram illustrates how information for specifying the traits of an organism is carried in DNA. The sequence of bases in DNA is used as a template for mRNA. The codons of mRNA specify the sequence of amino acids in a protein, and proteins play a key role in producing an organism's traits.

The Roles of RNA and DNA

You can compare the different roles played by DNA and RNA molecules in directing protein synthesis to the two types of plans used by builders. A master plan has all the information needed to construct a building. But builders never bring the valuable master plan to the building site, where it might be damaged or lost. Instead, they prepare inexpensive, disposable copies of the master plan called blueprints. The master plan is safely stored in an office, and the blueprints are taken to the job site. Similarly, the cell uses the vital DNA "master plan" to prepare RNA "blueprints." The DNA molecule remains within the safety of the nucleus, while RNA molecules go to the protein-building sites in the cytoplasm—the ribosomes.

Genes and Proteins

Gregor Mendel might have been surprised to learn that most genes contain nothing more than instructions for assembling proteins, as shown in **Figure 12–19.** He might have asked what proteins could possibly have to do with the color of a flower, the shape of a leaf, a human blood type, or the sex of a newborn baby.

The answer is that proteins have everything to do with these things. Remember that many proteins are enzymes, which catalyze and regulate chemical reactions. A gene that codes for an enzyme to produce pigment can control the color of a flower. Another gene produces an enzyme specialized for the production of red blood cell surface antigen. This molecule determines your blood type. Genes for certain proteins can regulate the rate and pattern of growth throughout an organism, controlling its size and shape. In short, proteins are microscopic tools, each specifically designed to build or operate a component of a living cell.

12–3 Section Assessment

1. **Key Concept** List the three main types of RNA.
2. **Key Concept** What happens during transcription?
3. **Key Concept** What happens during translation?
4. Describe the three main differences between RNA and DNA.
5. **Critical Thinking Applying Concepts** Using the genetic code, identify the amino acids that have the following messenger RNA strand codes: UGGCAGUGC.

Writing in Science

Creative Writing

An RNA molecule is looking for a job in a protein synthesis factory, and it asks you to write its résumé. This RNA molecule is not yet specialized and could, with some structural changes, function as either mRNA, tRNA, or rRNA. The résumé you create should reflect the qualifications needed for each type of RNA.

12-4 Mutations

BI 4.c. Students know how mutations in the DNA sequence of a gene may or may not affect the expression of the gene or the sequence of amino acids in the encoded protein.

Guide for Reading

Key Concept
- What are mutations?

Vocabulary
mutation
point mutation
frameshift mutation
polyploidy

Reading Strategy: Using Visuals Before you read, preview **Figure 12-20** and **Figure 12-21.** As you read, notice the changes that occur in gene and chromosomal mutations.

Now and then cells make mistakes in copying their own DNA, inserting an incorrect base or even skipping a base as the new strand is put together. These mistakes are called **mutations,** from a Latin word meaning "to change." **Mutations are changes in the genetic material.**

Kinds of Mutations

Like the mistakes that people make in their daily lives, mutations come in many shapes and sizes. Mutations that produce changes in a single gene are known as gene mutations. Those that produce changes in whole chromosomes are known as chromosomal mutations.

Gene Mutations Gene mutations involving changes in one or a few nucleotides are known as **point mutations,** because they occur at a single point in the DNA sequence. Point mutations include substitutions, in which one base is changed to another, as well as insertions and deletions, in which a base is inserted or removed from the DNA sequence.

Substitutions usually affect no more than a single amino acid. The effects of insertions or deletions can be much more dramatic. Remember that the genetic code is read in three-base codons. If a nucleotide is added or deleted, the bases are still read in groups of three, but now those groupings are shifted for every codon that follows, as shown in **Figure 12-20.** Changes like these are called **frameshift mutations** because they shift the "reading frame" of the genetic message. By shifting the reading frame, frameshift mutations may change every amino acid that follows the point of the mutation. Frameshift mutations can alter a protein so much that it is unable to perform its normal functions.

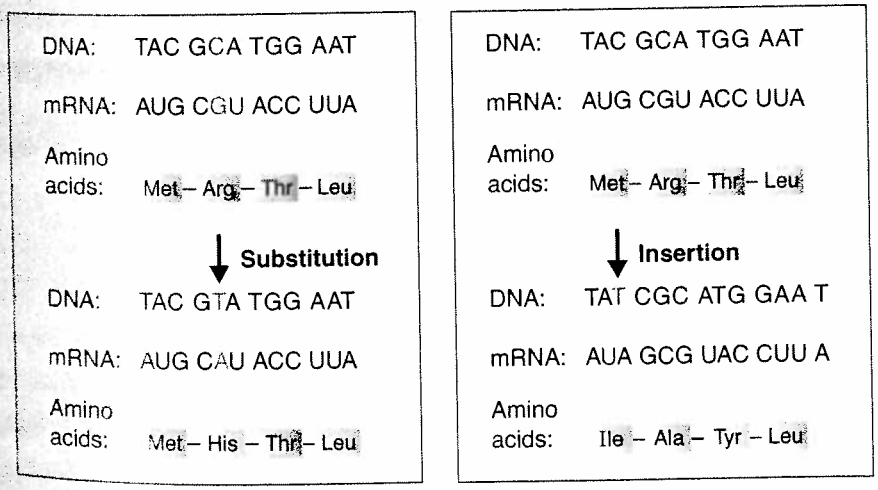


Figure 12-20 Gene mutations result from changes in a single gene. These diagrams illustrate the different types of mutations, or changes, in DNA. They also show how the mutations affect the amino acid sequences of the proteins for which they code. In a substitution (left), one base replaces another. In an insertion (center), an extra base is inserted into a base sequence. The loss of a single letter in a sentence (below) models the effects of the deletion of one base in a DNA sequence.

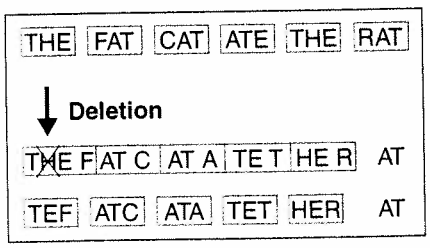
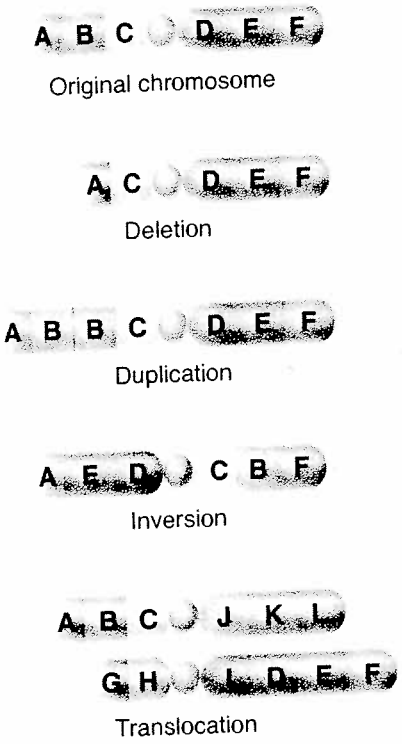


Figure 12–21
Chromosomal mutations involve changes in whole chromosomes. The illustration below shows four types of chromosomal mutations.



Chromosomal Mutations Chromosomal mutations involve changes in the number or structure of chromosomes. Such mutations may change the locations of genes on chromosomes, and may even change the number of copies of some genes.

Figure 12–21 shows four types of chromosomal mutations: deletions, duplications, inversions, and translocations. Deletions involve the loss of all or part of a chromosome, while duplications produce extra copies of parts of a chromosome. Inversions reverse the direction of parts of chromosomes, and translocations occur when part of one chromosome breaks off and attaches to another.

Significance of Mutations

Many, if not most, mutations are neutral, meaning that they have little or no effect on the expression of genes or the function of the proteins for which they code. Mutations that cause dramatic changes in protein structure or gene activity are often harmful, producing defective proteins that disrupt normal biological activities. However, mutations are also the source of genetic variability in a species. Some of this variation may be highly beneficial.

Mutations are the causes of many genetic disorders, including sickle cell disease and cystic fibrosis, both discussed in Chapter 14. Harmful mutations are also associated with many types of cancer. In contrast, beneficial mutations may produce proteins with new or altered activities that can be useful in changing environments. One such mutation produces resistance to HIV, the virus that causes AIDS.

Plant and animal breeders often take advantage of such beneficial mutations. For example, when a complete set of chromosomes fails to separate during meiosis, the gametes that result may produce triploid (3N) or tetraploid (4N) organisms. The condition in which an organism has extra sets of chromosomes is called **polyploidy.** Polyploid plants are often larger and stronger than diploid plants. Important crop plants have been produced in this way, including bananas and many citrus fruits.

12–4 Section Assessment

1. **Key Concept** What is a mutation?
2. What is the significance of mutations to living things?
3. What are two kinds of frameshift mutations?
4. What are four types of chromosomal mutations?
5. **Critical Thinking Inferring** The effects of a mutation are not always visible. How might a biologist determine whether a mutation has occurred, and if so, what type of mutation it is?

Writing in Science

Compare/Contrast Paragraph

Write a paragraph comparing and contrasting gene mutations and chromosomal mutations. *Hint:* To organize your ideas, use a compare/contrast table. The column heads might be *Definition, Types,* and *Effects.*

12-5 Gene Regulation

BI 4.d. Students know specialization of cells in multicellular organisms is usually due to different patterns of gene expression rather than to differences of the genes themselves.

Only a fraction of the genes in a cell are expressed at any given time. An expressed gene is a gene that is transcribed into RNA. How does the cell determine which genes will be expressed and which will remain "silent"? A close look at the structure of a gene provides some important clues.

At first glance, the DNA sequence of a gene is nothing more than a confusing jumble of the four letters that represent the bases in DNA. However, if we take the time to analyze those letters, patterns emerge. Molecular biologists have found that certain DNA sequences serve as promoters, binding sites for RNA polymerase. Others serve as start and stop signals for transcription. In fact, cells are filled with DNA-binding proteins that attach to specific DNA sequences and help to regulate gene expression. A typical gene might look something like **Figure 12–22.**

As we've seen, there is a promoter just to one side of the gene. But what are the "regulatory sites" next to the promoter? These are places where other proteins, binding directly to the DNA sequences at those sites, can regulate transcription. The actions of these proteins help to determine whether a gene is turned on or turned off.

Gene Regulation: An Example

How does an organism "know" whether to turn a gene on or off? The common bacterium *E. coli* provides us with a perfect example of how gene expression can be regulated. The 4288 protein-encoding genes in this bacterium include a cluster of three genes that are turned on or off together. A group of genes that operate together is known as an **operon.** Because these genes must be expressed in order for the bacterium to be able to use the sugar lactose as a food, they are called the *lac* operon.

Guide for Reading

Key Concepts

- How are *lac* genes turned off and on?
- How are most eukaryotic genes controlled?

Vocabulary

operon
operator
differentiation
hox gene

Reading Strategy: Outlining

Before you read, use the headings of the section to make an outline about gene regulation. As you read, fill in subtopics and smaller topics. Then, add phrases or a sentence after each subtopic to provide key information.

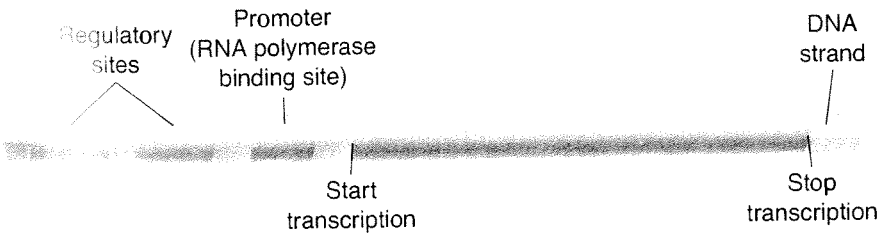
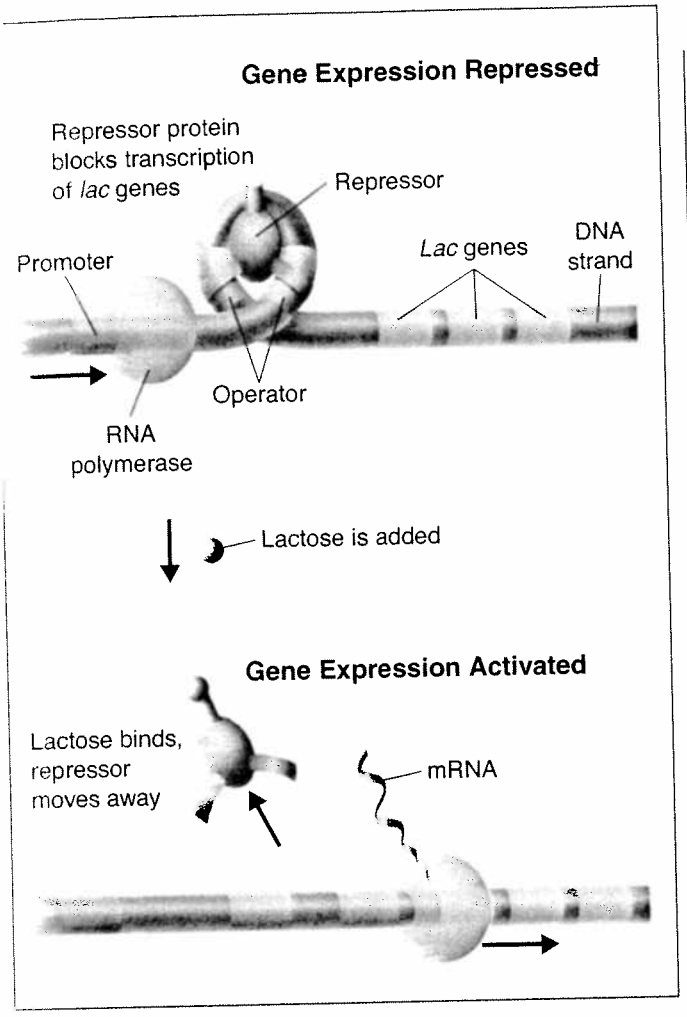


Figure 12–22 A typical gene includes start and stop signals, with the nucleotides to be translated in between. The DNA sequence shown is only a very small part of an actual gene. *What is the function of the promoter?*



▲ **Figure 12–23** **The *lac* genes in *E. coli* are turned off by repressors and turned on by the presence of lactose.** When lactose is not present, the repressor binds to the operator region, preventing RNA polymerase from beginning transcription. Lactose causes the repressor to be released from the operator region.

Why must *E. coli* turn on the *lac* genes in order to use lactose for food? Lactose is a compound made up of two simple sugars, galactose and glucose. To use lactose for food, the bacterium must take lactose across its cell membrane and then break the bond between glucose and galactose. These tasks are performed by proteins coded for by the genes of the *lac* operon. This means, of course, that if the bacterium is grown in a medium where lactose is the only food source, it must transcribe the genes and produce these proteins. If grown on another food source, such as glucose, it would have no need for these proteins.

Remarkably, the bacterium almost seems to "know" when the products of these genes are needed. **The *lac* genes are turned off by repressors and turned on by the presence of lactose.** This process tells us a great deal about how genes are regulated.

On one side of the operon's three genes are two regulatory regions. In the promoter (P), RNA polymerase binds and then begins transcription. The other region is the **operator** (O). *E. coli* cells contain several copies of a DNA-binding protein known as the *lac* repressor, which can bind to the O region. As **Figure 12–23** shows, when the *lac* repressor binds to the O region, RNA polymerase is prevented from beginning the process of transcription. In effect, the binding of the repressor protein turns the operon "off" by preventing the transcription of its genes.

If the repressor protein is always present, how are the *lac* genes turned on in the presence of lactose? Besides its DNA binding site, the *lac* repressor protein has a binding site for lactose itself. When lactose is added to the medium in which *E. coli* is growing, sugar molecules diffuse into the cell and bind to the repressor proteins. This causes the repressor protein to change shape in a way that causes the repressor to fall off the operator. Now, with the repressor no longer bound to the O site, RNA polymerase can bind to the promoter and transcribe the genes of the operon.

The *lac* operon shows one way in which prokaryotic genes are regulated. Many genes are regulated by repressor proteins, while others use proteins that speed transcription. Sometimes regulation occurs at the level of protein synthesis. Regardless of the system, the result is the same: Cells turn their genes on and off as needed.

CHECKPOINT *What is the operator?*

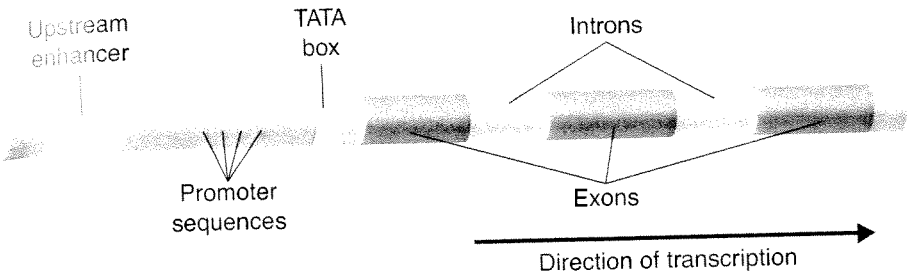


Figure 12–24 Many eukaryotic genes include a sequence called the TATA box that may help position RNA polymerase. **Eukaryotic genes have regulatory sequences that are more complex than prokaryotic genes.**

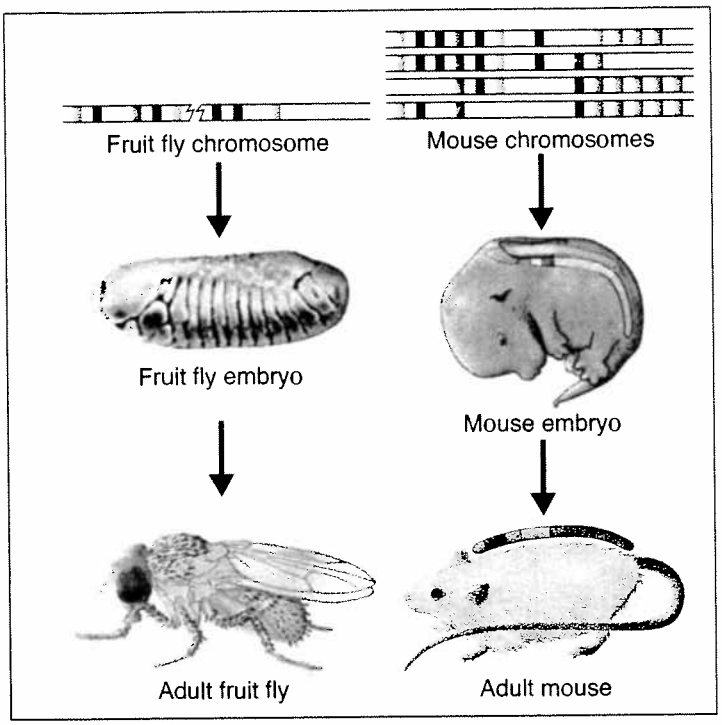
Eukaryotic Gene Regulation

The general principles of gene regulation in prokaryotes also apply to eukaryotic cells, although there are some important differences. Operons are generally not found in eukaryotes. **Most eukaryotic genes are controlled individually and have regulatory sequences that are much more complex than those of the *lac* operon.**

Figure 12–24 shows some of the features of a typical eukaryotic gene. One of the most interesting is a short region of DNA about 30 base pairs long, containing a sequence of TATATA or TATAAA, before the start of transcription. This region is found before so many eukaryotic genes that it even has a name: the "TATA box." The TATA box seems to help position RNA polymerase by marking a point just before the point at which transcription begins. Eukaryotic promoters are usually found just before the TATA box, and they consist of a series of short DNA sequences.

Genes are regulated in a variety of ways by enhancer sequences located before the point at which transcription begins. An enormous number of proteins can bind to different enhancer sequences, which is why eukaryotic gene regulation is so complex. Some of these DNA-binding proteins enhance transcription by opening up tightly packed chromatin. Others help to attract RNA polymerase. Still other proteins block access to genes, much like prokaryotic repressor proteins.

Why is gene regulation in eukaryotes more complex than in prokaryotes? Think for a moment about the way in which genes are expressed in a multicellular organism. The genes that code for liver enzymes, for example, are not expressed in nerve cells. Keratin, an important protein in skin cells, is not produced in blood cells. Cell specialization requires genetic specialization, but all of the cells in a multicellular organism carry the complete genetic code in their nucleus. Therefore, for proper overall function, only a tiny fraction of the available genes needs to be expressed in the appropriate cells of different tissues throughout the body. The complexity of gene regulation in eukaryotes makes this specificity possible.



▲ **Figure 12–25** In fruit flies, a series of hox genes along a chromosome determines the basic structure of the fly's body. Mice have very similar genes on four different chromosomes. The color bars along the mouse's back show the approximate body area affected by genes of the corresponding colors. **Interpreting Graphics** *What section of the bodies of flies and mice is coded by the genes shown in blue?*

Development and Differentiation

Regulation of gene expression is especially important in shaping the way a complex organism develops. Each of the specialized cell types found in the adult develops from the same fertilized egg cell. This means that cells don't just grow and divide during embryonic development; they also undergo **differentiation,** meaning they become specialized in structure and function. The study of genes that control development and differentiation is one of the most exciting areas in biology today.

A series of genes, known as the **hox genes,** control the differentiation of cells and tissues in the embryo. A mutation in one of these "master control genes" can completely change the organs that develop in specific parts of the body. Mutations affecting the hox genes in the fruit fly, *Drosophila,* for example, can replace the fly's antennae with legs growing on its head!

In flies, the hox genes are located side-by-side in a single cluster, as shown in **Figure 12–25.** Remarkably, similar clusters exist in the DNA of other animals, including humans. The function of the hox genes in humans seems to be almost the same—to tell the cells of the body how they should differentiate as the body grows. Careful control of expression in these genes is essential for normal development.

The striking similarity of genes that control development has a simple scientific explanation: Common patterns of genetic control exist because all these genes have descended from the genes of common ancestors. One such gene, called Pax 6, controls eye growth in *Drosophila.* A similar gene was found to guide eye growth in mice and other mammals. When a copy of the mouse gene was inserted into the "knee" of a *Drosophila* embryo, the resulting fruit fly grew an eye on its leg! The fly gene and the mouse gene are similar enough to trade places and still function—even though they come from animals that have not shared a common ancestor in at least 600 million years.

12–5 Section Assessment

1. **Key Concept** How is the *lac* operon regulated?
2. **Key Concept** Describe how most eukaryotic genes are controlled.
3. What genes control cell differentiation during development?
4. What is a promoter?
5. **Critical Thinking Comparing and Contrasting** How is the way hox genes are expressed in mice similar to the way they are expressed in fruit flies? How is it different?

Writing in Science

Making an Analogy

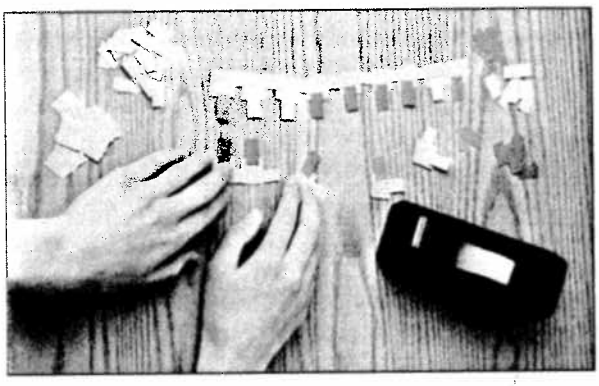
Make an analogy to demonstrate the different components of the *lac* operon. Then, explain in a short paragraph—using your analogy—how the *lac* operon works.

Exploration

BI 5.b, BIIE 7.e, BIIE 9.b, BIIE 1.g

Modeling DNA Replication

Living cells synthesize exact copies of DNA molecules that are passed on to each daughter cell during cell division. In this investigation, you will model DNA replication.



Problem How is DNA replicated?

Materials

- construction paper (tan, gray, green, yellow, red, and purple)
- metric ruler
- scissors
- transparent tape

Skills Using Models

Procedure

1. Cut out rectangles of construction paper in the sizes and colors indicated below:
   Sugars: 36 tan pieces, each 2 cm × 2 cm
   Phosphates: 36 gray pieces, each 1 cm × 2 cm
   Adenines (A): 12 green pieces, each 1 cm × 2 cm
   Thymines (T): 12 yellow pieces, each 1 cm × 2 cm
   Guanines (G): 6 red pieces, each 1 cm × 2 cm
   Cytosines (C): 6 purple pieces, each 1 cm × 2 cm
2. To model a nucleotide, tape together a phosphate group, a sugar, and a guanine (G) molecule (see **Figure 12–5**).
3. Assemble eight additional nucleotide models with the following nitrogenous bases: 3 thymines (T); 3 adenines (A); 2 cytosines (C).
4. To model a single strand of DNA, tape the sugar of each nucleotide to the phosphate group of the next nucleotide in the following order: G T T A C A A T C.
5. Construct a strand of DNA that is complementary to the first strand. Tape the nucleotides of the second strand together as you did in step 4. Record the positions of the bases in both strands of your model.
6. Place the two strands side by side so that their complementary nucleotides face each other. Do not tape the two strands together. Write "original" on each strand.
7. Separate the two strands. Simulate the action of DNA polymerase by constructing a new complementary strand for each original strand.
8. Tape the bases of each new strand to the complementary bases of its matching strand.

Analyze and Conclude

1. **Comparing and Contrasting** Compare the new double-stranded DNA models with your original DNA model. Are their nucleotide sequences identical?
2. **Using Models** After a cell's DNA is replicated, the cell may divide in two. Each new cell receives one copy of the original cell's DNA. According to your model, how are the new strands and the original strands divided between the two new cells?
3. **Drawing Conclusions** What problems would you expect to occur if DNA was not copied accurately as it is replicated?
4. **Evaluating** Do you consider this procedure an adequate model of DNA replication? Explain your answer.
5. **Using Models** Describe an alternative way of modeling DNA replication.

Go Further

Using Models Cells use the information in DNA to make proteins. First, part of the nucleotide sequence of DNA is copied into a complementary sequence of RNA in the process of transcription. Then, during translation, the cell uses information in the RNA to make proteins. Modify your model or make a new model to show how transcription and translation occur.

Chapter 12 Study Guide

12–1 DNA

Key Concepts BIIE 1.k

- Avery and other scientists discovered that DNA is the nucleic acid that stores and transmits the genetic information from one generation of an organism to the next.
- Hershey and Chase concluded that the genetic material of the bacteriophage was DNA.
- Watson and Crick's model of DNA was a double helix, in which two strands were wound around each other.

Vocabulary
transformation, p. 288 • bacteriophage, p. 289
nucleotide, p. 291 • base pairing, p. 294

12–2 Chromosomes and DNA Replication

Key Concept BI 5.b

- During DNA replication, the DNA molecule separates into two strands, and then produces two new complementary strands following the rules of base pairing. Each strand of the double helix of DNA serves as a template, or model, for the new strand.

Vocabulary
chromatin, p. 296 • histone, p. 296
replication, p. 299 • DNA polymerase, p. 299

12–3 RNA and Protein Synthesis

Key Concepts BI 1.d, BI 4.a, BI 4.b,

- There are three main types of RNA: messenger RNA, ribosomal RNA, and transfer RNA.
- During transcription, RNA polymerase binds to DNA and separates the DNA strands. RNA polymerase then uses one strand of DNA as a template from which nucleotides are assembled into a strand of RNA.
- During translation, the cell uses information from messenger RNA to produce proteins.

Vocabulary
gene, p. 300 • messenger RNA, p. 301
ribosomal RNA, p. 301
transfer RNA, p. 301 • transcription, p. 301
RNA polymerase, p. 301 • promoter, p. 301
intron, p. 302 • exon, p. 302 • codon, p. 302
translation, p. 304 • anticodon, p. 304

12–4 Mutations

Key Concept BI 4.c

- Mutations are changes in genetic material. Gene mutations result from changes in a single gene. Chromosomal mutations involve changes in whole chromosomes.

Vocabulary
mutation, p. 307 • point mutation, p. 307
frameshift mutation, p. 307 • polyploidy, p. 308

12–5 Gene Regulation

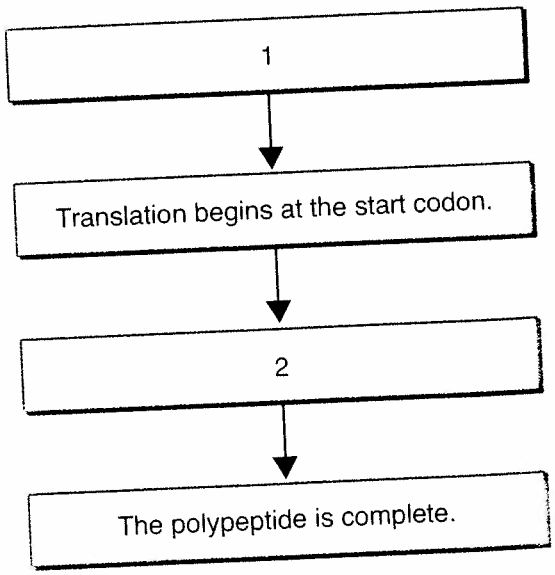
Key Concepts BI 4.d

- The *lac* genes are turned off by repressors and turned on by the presence of lactose.
- Most eukaryotic genes are controlled individually and have regulatory sequences that are much more complex than those of the *lac* operon.

Vocabulary
operon, p. 309 • operator, p. 310
differentiation, p. 312 • hox gene, p. 312

Thinking Visually

Using the information in this chapter, complete the following flowchart about protein synthesis:



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Reviewing Content

Choose the letter that best answers the question or completes the statement.

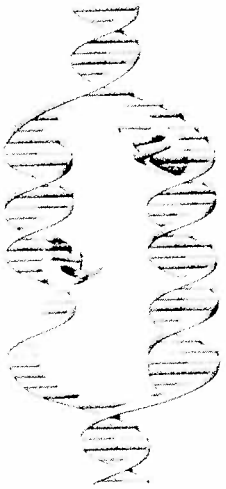
1. The process by which one strain of bacteria is apparently changed into another strain is called
   a. transcription. c. transformation.
   b. translation. d. replication.

2. Bacteriophages are
   a. tiny bacteria. c. coils of RNA.
   b. enzymes. d. viruses.

3. A nucleotide does NOT contain
   a. a 5-carbon sugar.
   b. polymerase.
   c. a nitrogen base.
   d. a phosphate group.

4. In prokaryotes, DNA molecules are located in the
   a. nucleus. c. cytoplasm.
   b. ribosome. d. histone.

5. The diagram below shows the process of DNA



   a. replication. c. translation.
   b. transcription. d. transformation.

6. The main enzyme involved in linking individual nucleotides into DNA molecules is
   a. transfer RNA. c. RNA polymerase.
   b. ribose. d. DNA polymerase.

7. The process by which the genetic code of DNA is copied into a strand of RNA is called
   a. translation. c. transformation.
   b. transcription. d. replication.

8. In messenger RNA, each codon specifies a particular
   a. nucleotide. c. amino acid.
   b. purine. d. pyrimidine.

9. Changes in the DNA sequence that affect genetic information are known as
   a. replications. c. transformations.
   b. mutations. d. prokaryotes.

10. An expressed gene is one that
    a. functions as a promoter.
    b. is transcribed into RNA.
    c. codes for only one amino acid.
    d. is made of mRNA.

Understanding Concepts

11. As scientists tried to discover the nature of genes, what three critical gene functions had they identified?

12. Describe the components and structure of a DNA nucleotide.

13. Explain how Chargaff's rules helped Watson and Crick model DNA.

14. What is meant by the term *base pairing*? How is base pairing involved in DNA replication?

15. Describe the appearance of DNA in a typical prokaryotic cell.

16. Explain the process of replication. When a DNA molecule is replicated, how do the new molecules relate to the original molecule?

17. Describe the relationship between DNA, chromatin, histones, and nucleosomes.

18. What is the difference between exons and introns?

19. What is a codon?

20. What is an anticodon? How does it function?

21. If a code on a DNA molecule for a specific amino acid is CTA, what would be the messenger RNA codon? The transfer RNA anticodon?

22. Explain why controlling the proteins in an organism controls the organism's characteristics.

23. Name two major types of mutations. What do they have in common? How are they different? Give an example of each.

24. Describe how a TATA box helps position RNA polymerase in a eukaryotic cell.

25. Describe the role of an operon in a prokaryotic cell, and give an example of how an operon works.

Critical Thinking

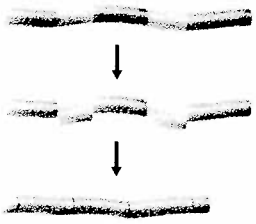
26. **Interpreting Graphics** Look back at Griffith's experiment, shown in **Figure 12–2.** Describe the occasion in which the bacterial DNA withstood conditions that killed the bacteria. Describe what happened to the DNA from that point until the end of the experiment.

27. **Using Models** Evaluate Watson and Crick's model of the DNA molecule. How adequately does it represent the structure of DNA?

28. **Using Analogies** Is photocopying a document similar to DNA replication? Think of the original materials, the copying process, and the final products. Explain how the two processes are alike. Identify major differences.

29. **Applying Concepts** Suppose you start with two DNA strands: ACCGTCAC and TCGCACGT. Use the "rules" of base pairing to list the bases on messenger RNA strands transcribed from those DNA strands.

30. **Predicting** Examine the first intron in the diagram below. What difference would result in the protein produced by the messenger RNA if that intron were not removed but instead functioned as an exon?



31. **Using Analogies** The word *transcribe* means "to write out," and the word *translate* means "to express in another language." Review the meanings of *transcription* and *translation* in genetics. How do the technical meanings of these words relate to meanings of the words in ordinary language?

32. **Inferring** Rosalind Franklin's X-ray patterns showed that the distance between the two phosphate-sugar "backbones" of a DNA molecule is the same throughout the length of the molecule. How did that information help Watson and Crick determine how the bases are paired?

33. **Comparing and Contrasting** How does the possible impact of a chromosomal mutation that occurs during meiosis differ from that of a similar event that occurs during mitosis of a body cell not involved in reproduction?

34. **Predicting** A researcher identifies the nucleotide sequence AAC in a long strand of RNA inside a nucleus. In the genetic code, AAC codes for the amino acid asparagine. When that RNA becomes involved in protein synthesis, will asparagine necessarily appear in the protein? Explain.

Focus on the BIG Idea

Information and Heredity Recall what you learned about mitosis in Chapter 10 and meiosis in Chapter 11. Describe what happens to a cell's DNA during each of these processes.

Writing in Science

Recall that Gregor Mendel concluded that factors, which we now call genes, determine the traits that are passed from one generation to the next. Imagine that you could send a letter backwards in time to Mendel. Write a letter to him in which you explain what a gene consists of in molecular terms. In your letter, you will need to explain, briefly, what DNA and proteins are. (*Hint:* Review Chapter 2 for the definition of protein.)

Performance-Based Assessment

Make a Model Make a three-dimensional model representing protein synthesis. Your "protein" should be a sequence of three different amino acids. Show the DNA molecule and the related RNA molecules that would be involved in producing your protein.

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Test-Taking Tip When asked to find the solution to a problem, such as the complementary sequence of DNA or RNA, first solve the problem on scratch paper. Then, compare your answer with the options provided.

Directions: Choose the letter that best answers the question or completes the statement.

1. During replication, which sequence of nucleotides would bond with the DNA sequence TATGA? **BI 5.b**
   A TATGA **C** ATACT
   B UAUGA **D** AUAGA

2. In which of the following ways does RNA differ from DNA? **BI 5.a**
   A RNA contains uracil and deoxyribose.
   B RNA contains ribose and thymine.
   C RNA contains uracil and ribose.
   D RNA contains adenine and ribose.

3. Which of the following nucleotide(s) bond(s) with adenine? **BI 5.b**
   A thymine only
   B uracil only
   C cytosine and guanine
   D thymine and uracil

4. The process of decoding mRNA into a polypeptide chain is known as **BI 1.d**
   A transformation.
   B transpiration.
   C translation.
   D transcription.

5. Which of the following does NOT describe the structure of DNA? **BI 5.a**
   A double helix
   B nucleotide polymer
   C sugar-phosphate backbone
   D contains adenine-uracil pairs

6. What did Hershey and Chase's work show?
   A Genes are probably made of DNA.
   B Genes are probably made of protein.
   C Genes are made of both DNA and protein.
   D Viruses contain DNA but not protein.

7. Anticodons are part of the structure of
   A DNA.
   B messenger RNA.
   C transfer RNA.
   D ribosomal RNA.

Questions 8–9

A scientist analyzed several DNA samples from exons to determine the relative proportions of purine and pyrimidine bases. Her data are summarized in the table below.

Percentages of Bases in Three Samples

Sample	G	C	A	T
A	35	35	15	15
B	40	10	40	10
C	25	25	25	25

8. Which sample(s) support(s) the base-pairing rules? **BI 5.b**
   A Sample A only **C** Sample C only
   B Sample B only **D** Samples A and C

9. If the scientist had analyzed mRNA rather than DNA, what percentage of uracil would you expect to find in Sample B? **BI 5.b**
   A 10 **C** 35
   B 25 **D** 40

Questions 10–12 Each of the lettered choices below refers to the following numbered statements. Select the best lettered choice.

A Mutation **C** Genetic code
B Double helix **D** Transcription

10. RNA molecules are produced by copying part of the nucleotide sequence of DNA into a complementary sequence in RNA **BI 1.d**

11. Structure of DNA **BI 5.a**

12. Heritable change in the DNA sequence that affects genetic information **BI 4.c**