The 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?

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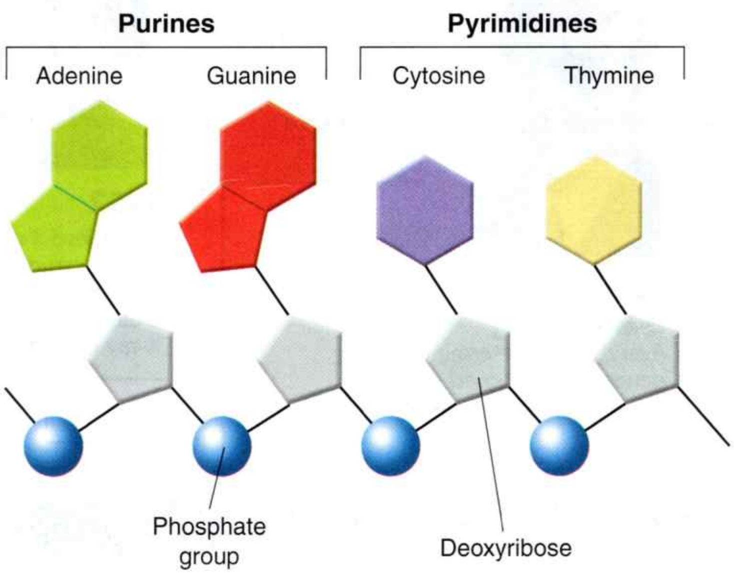
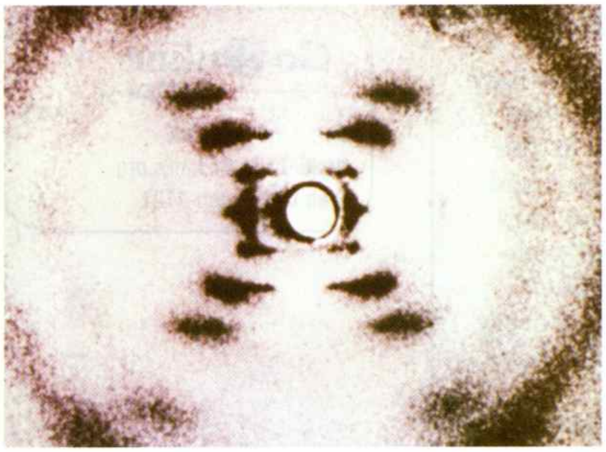


◀ **Figure 12–5** DNA is made up of nucleotides. Each nucleotide has three parts: a deoxyribose molecule, a phosphate group, and a nitrogenous base. There are four different bases in DNA: adenine, guanine, cytosine, and thymine. **Interpreting Graphics** ***How are the nucleotides joined together to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

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.

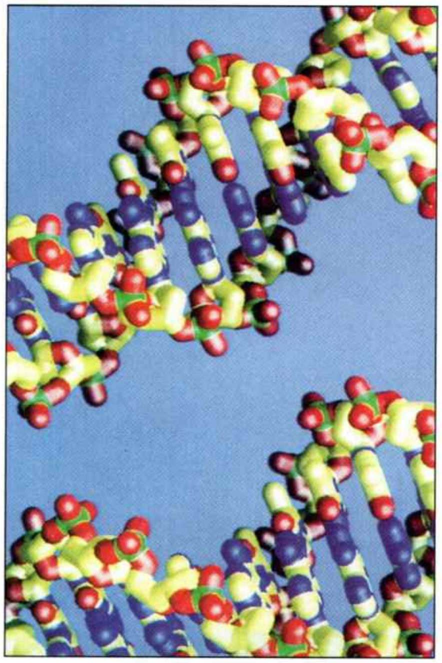
1960
Sydney Brenner
Brenner and other scientists show the existence of messenger RNA.

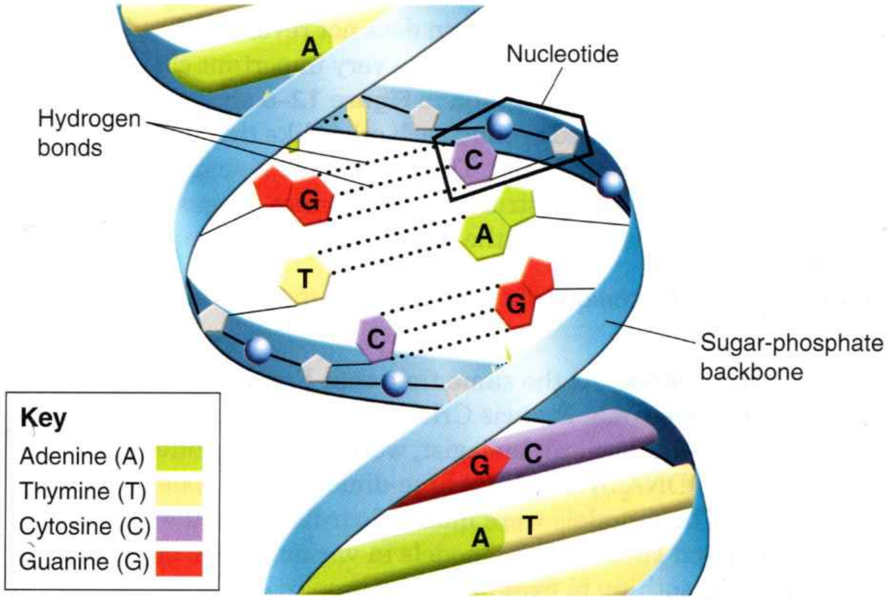
1977
Walter Gilbert
Gilbert, Allan Maxam, and Frederick Sanger develop methods to read the DNA sequence.

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

1950 1975 2000

Figure 12–7 **DNA is a double helix in which two strands are wound around each other.** Each strand is made up of a chain of nucleotides. The two strands are held together by hydrogen bonds between adenine and thymine and between guanine 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

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?

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.

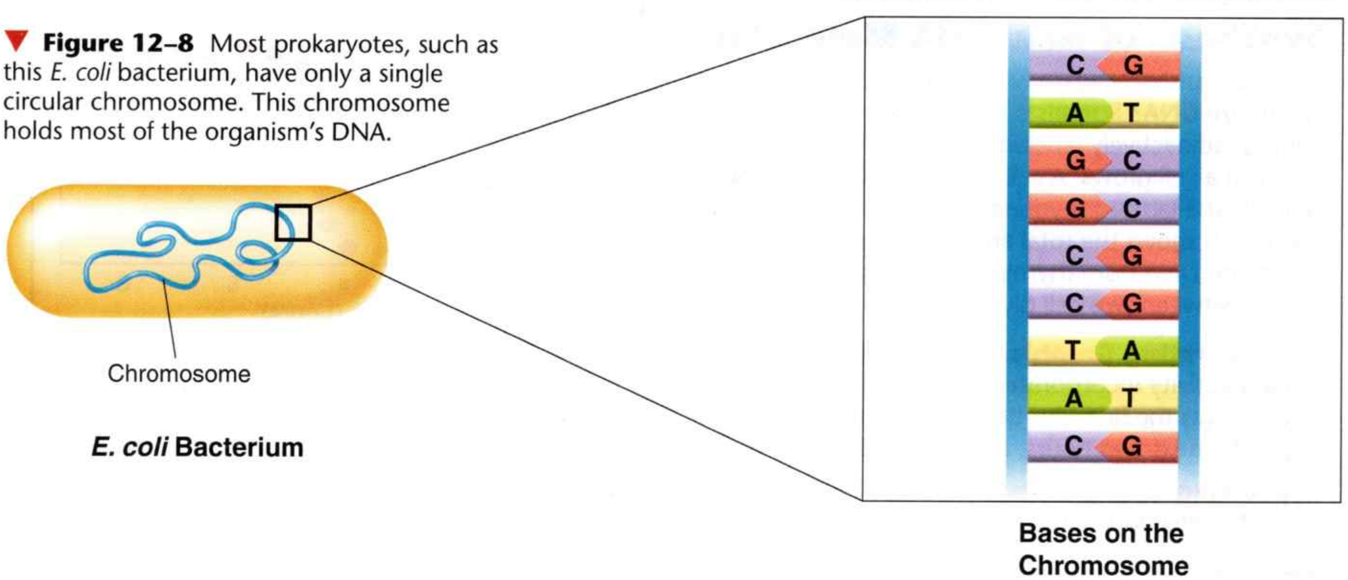
Guide for Reading

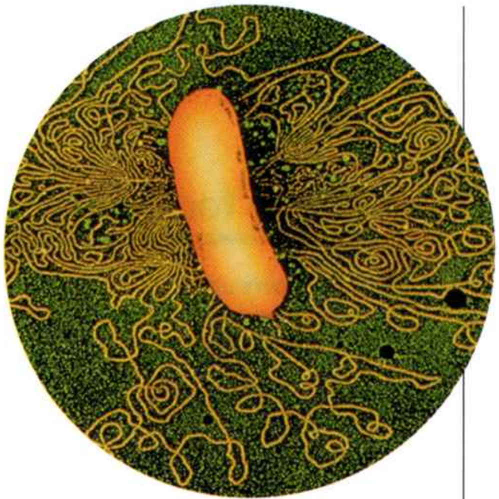
Key Concept
- What happens during DNA replication?

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.

▼ **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.

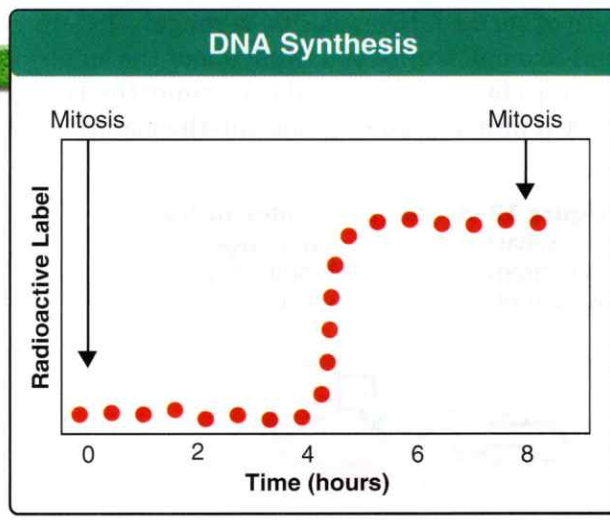
Eukaryotic chromosomes contain both DNA and protein, tightly packed together to form a substance called **chromatin.** Chromatin consists of DNA that is tightly coiled around proteins called **histones,** as shown in **Figure 12–10.** Together, the DNA and histone molecules form a beadlike structure 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.

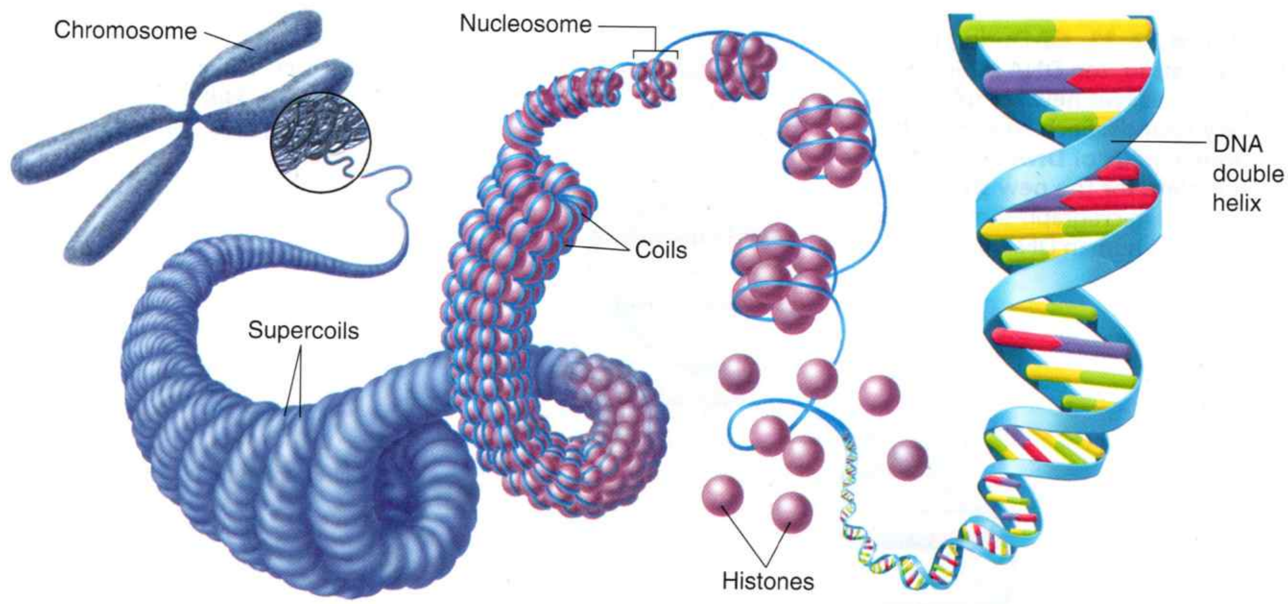
Analyzing Data

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.

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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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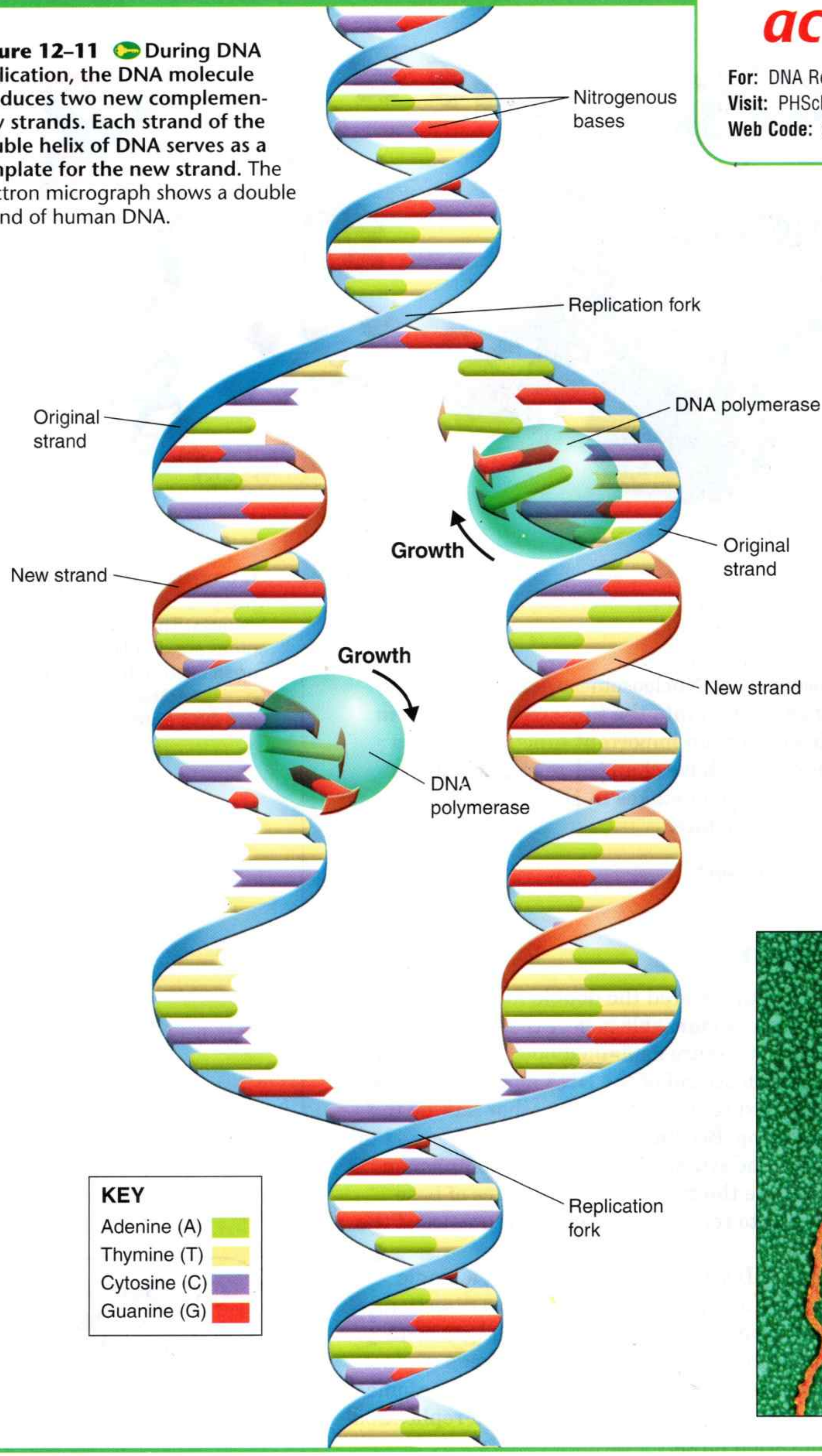

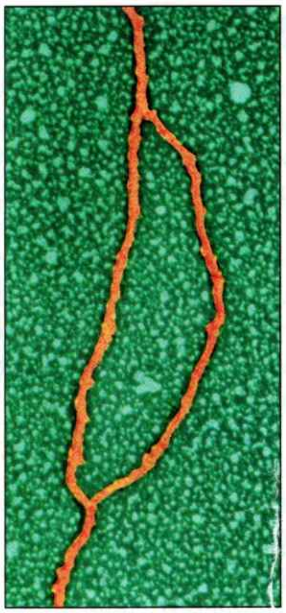

Duplicating DNA Before a cell divides, it duplicates its DNA in a copying process called **replication.** This process ensures that each resulting cell will have a complete set of DNA molecules. **During DNA replication, the DNA molecule separates into two strands, and then produces two new complementary 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.

12–2 Section Assessment

1. **Key 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 Comparing and Contrasting** 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.)