12 DNA

Big ideas

Information and Heredity, Cellular Basis of Life

Q: What is the structure of DNA, and how does it function in genetic inheritance?

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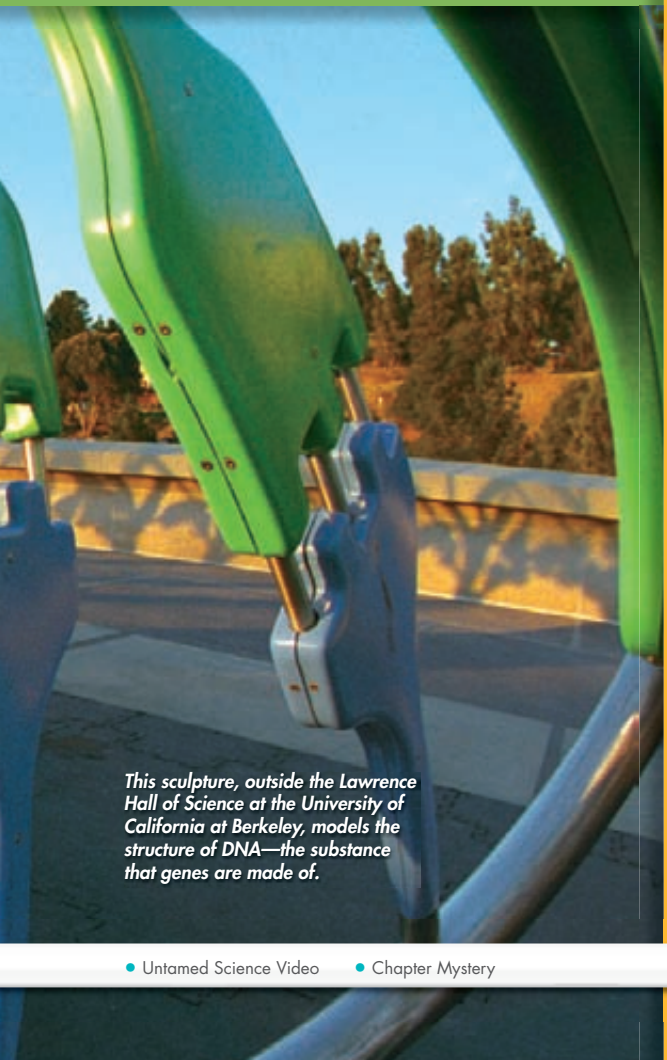
INSIDE:



This sculpture, outside the Lawrence Hall of Science at the University of California at Berkeley, models the structure of DNA—the substance that genes are made of.

- Untamed Science Video
- Chapter Mystery

CHAPTER MYSTERY

UV LIGHT

"Put on your sunscreen!" This familiar phrase can be heard at most beaches on a sunny day. It's an important directive, though, because sunlight—for all its beneficial effects—can readily damage the skin. The most dangerous wavelengths of sunlight are the ones we can't see: the ultraviolet (UV) region of the electromagnetic spectrum. Not only can excess exposure to UV light damage skin cells, it can cause a deadly form of skin cancer that kills nearly 10,000 Americans each year. Why is UV light so dangerous? How can these particular wavelengths of light damage our cells to the point of causing cell death and cancer? As you read this chapter, look for clues to help you solve the question of why UV light is so damaging to skin cells. Then, solve the mystery.

Never Stop Exploring Your World. Finding the connection between UV light and DNA is only the beginning. Take a video field trip with the ecogeeks of Untamed Science to see where the mystery leads.

Untamed Science™

12.1 Identifying the Substance of Genes

Key Questions

- ***What clues did bacterial transformation yield about the gene?***
- ***What role did bacterial viruses play in identifying genetic material?***
- ***What is the role of DNA in heredity?***

Vocabulary

transformation
bacteriophage

Taking Notes

Flowchart As you read this section, make a flowchart that shows how scientists came to understand the molecule known as DNA.

THINK ABOUT IT How do genes work? To answer that question, the first thing you need to know is what genes are made of. After all, you couldn't understand how an automobile engine works without understanding what the engine is made of and how it's put together. So, how would you go about figuring out what molecule or molecules go into making a gene?

Bacterial Transformation

What clues did bacterial transformation yield about the gene?

In the first half of the twentieth century, biologists developed the field of genetics to the point where they began to wonder about the nature of the gene itself. To truly understand genetics, scientists realized they first had to discover the chemical nature of the gene. If the molecule that carries genetic information could be identified, it might be possible to understand how genes actually control the inherited characteristics of living things.

Like many stories in science, the discovery of the chemical nature of the gene began with an investigator who was actually looking for something else. In 1928, the 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 the serious lung disease known as pneumonia.

Griffith had isolated two very similar types of bacteria from mice. These were actually two different varieties, or strains, of the same bacterial species. Both strains grew very well in culture plates in Griffith's lab, but only one of them caused pneumonia. The disease-causing bacteria (S strain) grew into smooth colonies on culture plates, whereas the harmless bacteria (R strain) produced colonies with rough edges. The difference in appearance made the two strains easy to tell apart.

Griffith's Experiments When Griffith injected mice with disease-causing bacteria, the mice developed pneumonia and died. When he injected mice with harmless bacteria, the mice stayed healthy. Griffith wondered what made the first group of mice get pneumonia. Perhaps the S-strain bacteria produced a toxin that made the mice sick? To find out, he ran the series of experiments shown in **Figure 12–1.** First, Griffith took a culture of the S strain, heated the cells to kill them, then injected the heat-killed bacteria into laboratory mice. The mice survived, suggesting that the cause of pneumonia was not a toxin from these disease-causing bacteria.

In Griffith's next experiment, he mixed the heat-killed, S-strain bacteria with live, harmless bacteria from the R strain. This mixture he injected into laboratory mice. By themselves, neither type of bacteria should have made the mice sick. To Griffith's surprise, however, the injected mice developed pneumonia, and many died. When he examined the lungs of these mice, he found them to be filled not with the harmless bacteria, but with the disease-causing bacteria. How could that happen if the S-strain cells were dead?

Transformation Somehow, the heat-killed bacteria passed their disease-causing ability to the harmless bacteria. Griffith reasoned that, when he mixed the two types of bacteria together, some chemical factor transferred from the heat-killed cells of the S strain into the live cells of the R strain. This chemical compound, he hypothesized, must contain information that could change harmless bacteria into disease-causing ones. He called this process **transformation,** because one type of bacteria (the harmless form) had been changed permanently into another (the disease-causing form). Because the ability to cause disease was inherited by the offspring of the transformed bacteria, Griffith concluded that the transforming factor had to be a gene.

In Your Notebook *Write a summary of Griffith's experiments.*

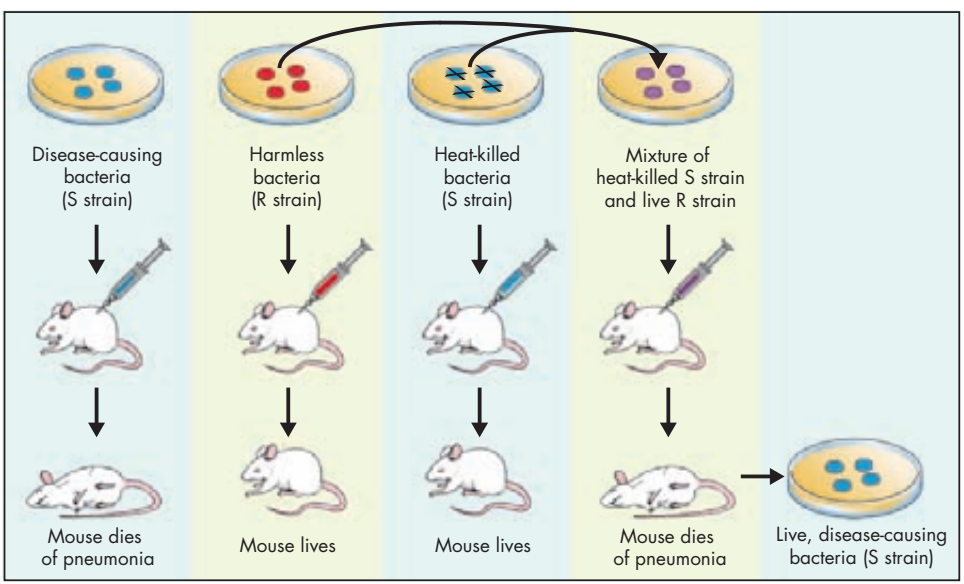


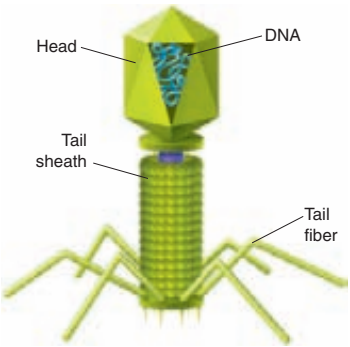
FIGURE 12–1 Griffith's Experiments Griffith injected mice with four different samples of bacteria. When injected separately, neither heat-killed, disease-causing bacteria nor live, harmless bacteria killed the mice. The two strains injected together, however, caused fatal pneumonia. From this experiment, Griffith inferred that genetic information could be transferred from one bacterial strain to another. **Infer** ***Why did Griffith test to see whether the bacteria recovered from the sick mice in his last experiment would produce smooth or rough colonies in a petri dish?***

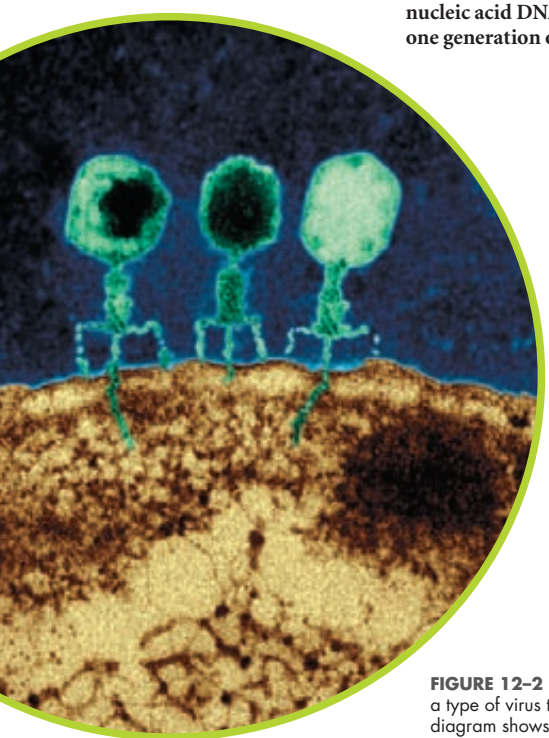
The Molecular Cause of Transformation In 1944, a group of scientists at the Rockefeller Institute in New York decided to repeat Griffith's work. Led by the Canadian biologist Oswald Avery, the scientists wanted to determine which molecule in the heat-killed bacteria was most important for transformation. They reasoned that if they could find this particular molecule, it might reveal the chemical nature of the gene.

Avery and his team extracted a mixture of various molecules from the heat-killed bacteria. They carefully treated this mixture with enzymes that destroyed proteins, lipids, carbohydrates, and some other molecules, including the nucleic acid RNA. Transformation still occurred. Clearly, since those molecules had been destroyed, none of them could have been responsible for transformation.

Avery's team repeated the experiment one more time. This time, they used enzymes that would break down a different nucleic acid—DNA. When they destroyed the DNA in the mixture, transformation did not occur. There was just one possible explanation for these results: *DNA was the transforming factor.* **By observing bacterial transformation, Avery and other scientists discovered that the nucleic acid DNA stores and transmits genetic information from one generation of bacteria to the next.**

T4 Bacteriophage





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Bacterial Viruses

What role did bacterial viruses play in identifying genetic material?

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 the experiments relating to the discovery made by Avery's team was performed in 1952 by two American scientists, Alfred Hershey and Martha Chase. They collaborated in studying viruses—tiny, nonliving particles that can infect living cells.

Bacteriophages A **bacteriophage** is a kind of virus that infects bacteria. When a bacteriophage enters a bacterium, it attaches to the surface of the bacterial cell and injects its genetic information into it, as shown in **Figure 12–2.** The viral genes act to produce many new bacteriophages, which gradually destroy the bacterium. When the cell splits open, hundreds of new viruses burst out.

FIGURE 12–2 Bacteriophages A bacteriophage is a type of virus that infects and kills bacteria. The top diagram shows a bacteriophage known as T4. The micrograph shows three T2 bacteriophages (green) invading an *E. coli* bacterium (gold).
Compare and Contrast ***How large are viruses compared with bacteria?***

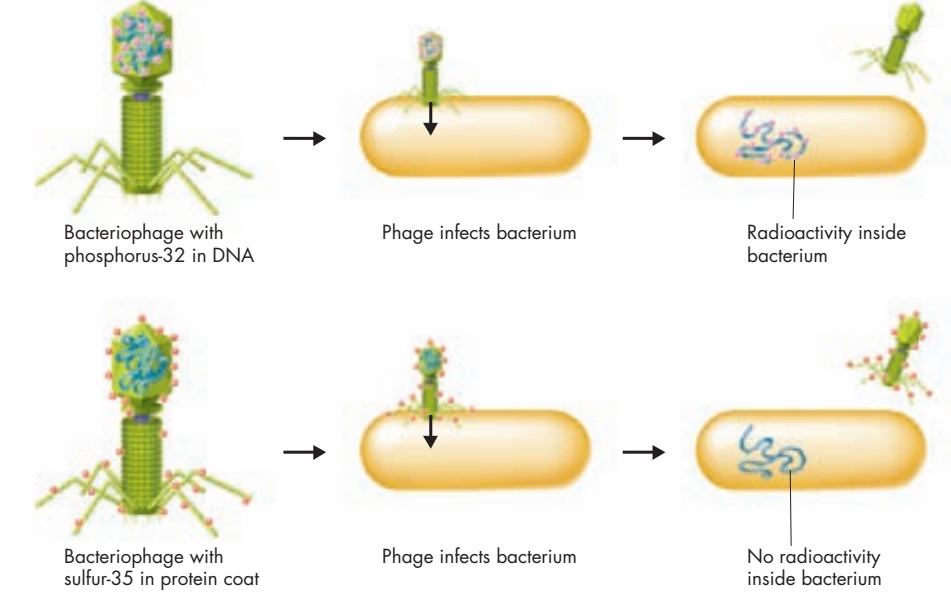

FIGURE 12–3 Hershey-Chase Experiment Alfred Hershey and Martha Chase used different radioactive markers to label the DNA and proteins of bacteriophages. The bacteriophages injected only DNA, not proteins, into bacterial cells.

The Hershey-Chase Experiment Hershey and Chase studied a bacteriophage that was composed of a DNA core and a protein coat. They wanted to determine which part of the virus—the protein coat or the DNA core—entered the bacterial cell. Their results would either support or disprove Avery's finding that genes were made of DNA.

The pair 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. Therefore, these radioactive substances could be used as markers, enabling the scientists to tell which molecules actually entered the bacteria, carrying the genetic information of the virus. If they found radioactivity from ^{35}S in the bacteria, it would mean that the virus's protein coat had been injected into the bacteria. If they found ^{32}P, then the DNA core had been injected.

The two scientists mixed the marked viruses with bacterial cells. 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. **Figure 12–3** shows the steps in this experiment. What were the results? 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 indeed DNA, not protein. **Hershey and Chase's experiment with bacteriophages confirmed Avery's results, convincing many scientists that DNA was the genetic material found in genes—not just in viruses and bacteria, but in all living cells.**

In Your Notebook *Identify the independent and dependent variables in the Hershey-Chase experiment, and list some possible control variables.*

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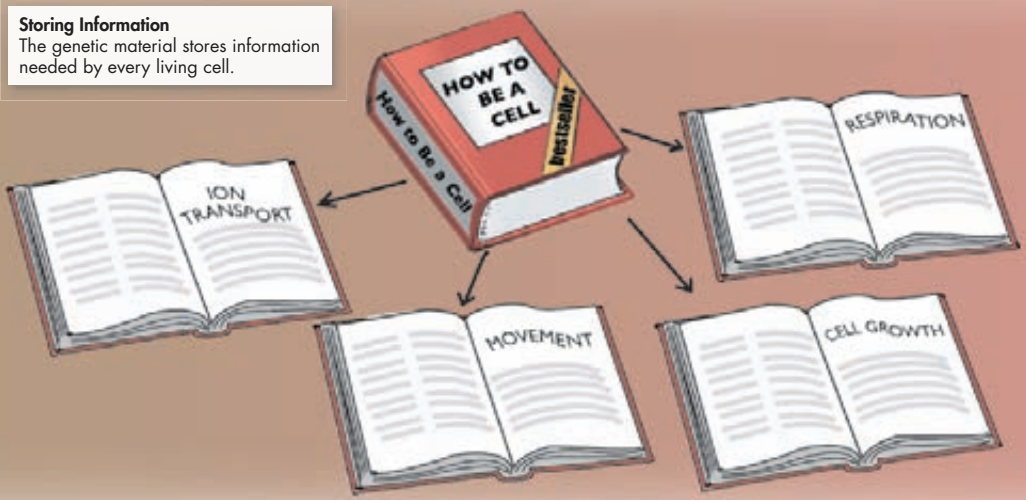

VISUAL ANALOGY

THE MAIN FUNCTIONS OF DNA

FIGURE 12–4 Like DNA, the book in this diagram contains coded instructions for a cell to carry out important biological processes, such as how to move or transport ions. The book, like DNA, can also be copied and passed along to the next generation. These three tasks—storing, copying, and transmitting information—are also the three main functions of DNA.

The Role of DNA

What is the role of DNA in heredity?

You might think that scientists would have been satisfied knowing that genes were made of DNA, but that was not the case at all. Instead, they wondered how DNA, or any molecule for that matter, could do the critical things that genes were known to do. The next era of study began with one crucial assumption. **The DNA that makes up genes must be capable of storing, copying, and transmitting the genetic information in a cell.** These three functions are analogous to the way in which you might share a treasured book, as pictured in **Figure 12–4.**

Storing Information The foremost job of DNA, as the molecule of heredity, is to store information. The genes that make a flower purple must somehow carry the information needed to produce purple pigment. Genes for blood type and eye color must have the information needed for their jobs as well, and other genes have to do even more. Genes control patterns of development, which means that the instructions that cause a single cell to develop into an oak tree, a sea urchin, or a dog must somehow be written into the DNA of each of these organisms.

Copying Information Before a cell divides, it must make a complete copy of every one of its genes. To many scientists, the most puzzling aspect of DNA was how it could be copied. The solution to this and other puzzles had to wait until the structure of the DNA molecule became known. Within a few weeks of this discovery, a copying mechanism for the genetic material was put forward. You will learn about this mechanism later in the chapter.

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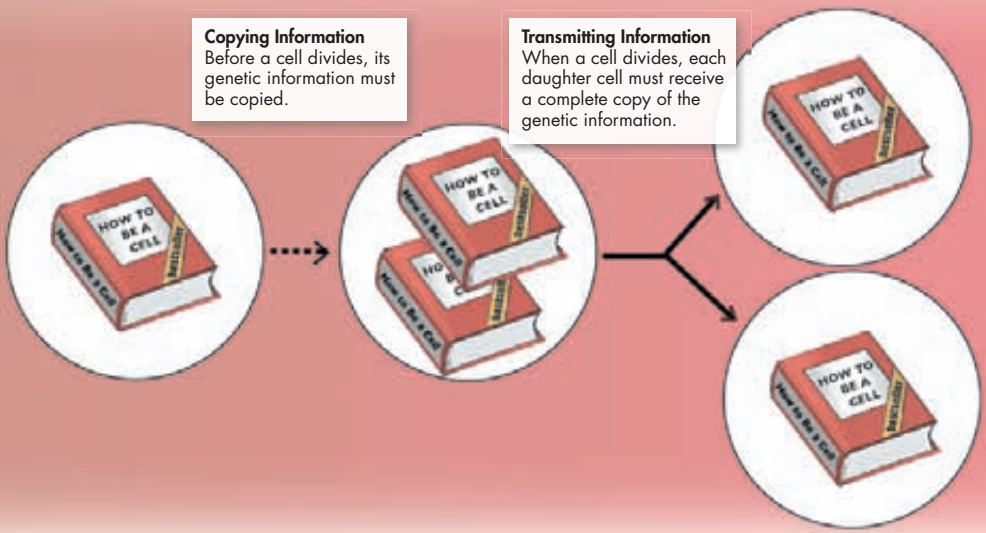

Transmitting Information As Mendel's work had shown, genes are transmitted from one generation to the next. Therefore, DNA molecules must be carefully sorted and passed along during cell division. Such careful sorting is especially important during the formation of reproductive cells in meiosis. Remember, the chromosomes of eukaryotic cells contain genes made of DNA. The loss of any DNA during meiosis might mean a loss of valuable genetic information from one generation to the next.

12.1 Assessment

Review Key Concepts

1. a. Review List the conclusions that Griffith and Avery drew from their experiments.

b. Identify Variables What was the experimental variable that Avery used when he repeated Griffith's work?

2. a. Review What conclusion did Hershey and Chase draw from their experiments?

b. Infer 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?

3. a. Review What are the three key roles of DNA?

b. Apply Concepts Why would the storage of genetic information in genes help explain why chromosomes are separated so carefully during mitosis?

Apply the Big idea

Science as a Way of Knowing

4. Choose either Griffith, Avery, or Hershey and Chase, and develop a flowchart that shows how that scientist or team of scientists used various scientific methods. Be sure to identify each method. You may use your flowchart from Taking Notes as a guide. If you need to, refer to the descriptions of scientific methods in Chapter 1.

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12.2 The Structure of DNA

Key Questions

- ***What are the chemical components of DNA?***
- ***What clues helped scientists solve the structure of DNA?***
- ***What does the double-helix model tell us about DNA?***

Vocabulary

base pairing

Taking Notes

Outline As you read, find the key ideas for the text under each green heading. Write down a few key words from each main idea. Then, use these key words to summarize the information about DNA.

THINK ABOUT IT It's one thing to say that the molecule called DNA carries genetic information, but it would be quite another thing to explain how it could do this. DNA must not only specify how to assemble proteins, but how genes can be replicated and inherited. DNA has to be a very special molecule, and it's got to have a very special structure. As we will see, understanding the structure of DNA has been the key to understanding how genes work.

The Components of DNA

What are the chemical components of DNA?

Deoxyribonucleic acid, or DNA, is a unique molecule indeed. **DNA is a nucleic acid made up of nucleotides joined into long strands or chains by covalent bonds.** Let's examine each of these components more closely.

Nucleic Acids and Nucleotides

As you may recall, nucleic acids are long, slightly acidic molecules originally identified in cell nuclei. Like many other macromolecules, nucleic acids are made up of smaller subunits, linked together to form long chains. Nucleotides are the building blocks of nucleic acids. **Figure 12–5** shows the nucleotides in DNA. These nucleotides are made up of three basic components: a 5-carbon sugar called deoxyribose, a phosphate group, and a nitrogenous base.

Nitrogenous Bases and Covalent Bonds

Nitrogenous bases, simply put, are bases that contain nitrogen. DNA has four kinds of nitrogenous bases: adenine (AD uh neen), guanine (GWAH neen), cytosine (SY tuh zeen), and thymine (THY meen). Biologists often refer to the nucleotides in DNA by the first letters of their base names: A, G, C, and T. The nucleotides in a strand of DNA are joined by covalent bonds formed between the sugar of one nucleotide and the phosphate group of the next. The nitrogenous bases stick out sideways from the nucleotide chain. The nucleotides can be joined together in any order, meaning that any sequence of bases is possible. These bases, by the way, have a chemical structure that makes them especially good at absorbing ultraviolet (UV) light. In fact, we can determine the amount of DNA in a solution by measuring the amount of light it absorbs at a wavelength of 260 nanometers (nm), which is in the UV region of the electromagnetic spectrum.

MYSTERY CLUE

The energy from UV light can excite electrons in the absorbing substance to the point where the electrons cause chemical changes. What chemical changes might occur in the nitrogenous bases of DNA?

If you don't see much in **Figure 12–5** that could explain the remarkable properties of DNA, 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 sequences, so it was possible they could carry coded genetic information. However, so could many other molecules, at least in principle. Biologists wondered if there were something more to the structure of DNA.

Solving the Structure of DNA

What clues helped scientists solve the structure of DNA?

Knowing that DNA is made from long chains of nucleotides was only the beginning of understanding the structure of this molecule. The next step required an understanding of the way in which those chains are arranged in three dimensions.

Chargaff's Rule One of the puzzling facts about DNA was a curious relationship between its nucleotides. Years earlier, Erwin Chargaff, an Austrian-American biochemist, had discovered that the percentages of adenine [A] and thymine [T] bases are almost equal in any sample of DNA. The same thing is true for the other two nucleotides, guanine [G] and cytosine [C]. The observation that [A] = [T] and [G] = [C] became known as "Chargaff's rule." 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.

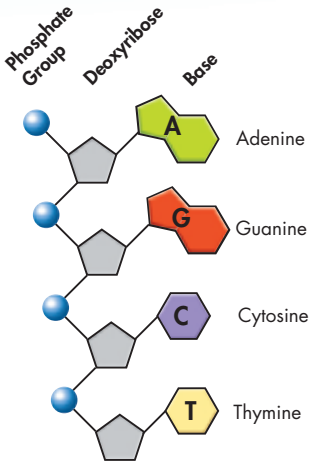


FIGURE 12–5 DNA Nucleotides DNA is made up of nucleotides, each with a deoxyribose molecule, a phosphate group, and a nitrogen-containing base. The four bases are adenine (A), guanine (G), cytosine (C), and thymine (T).
Interpret Visuals ***How are these four nucleotides joined together to form part of a DNA chain?***

Analyzing Data

Base Percentages

In 1949, Erwin Chargaff discovered that the relative amounts of A and T, and of G and C, are almost always equal. The table shows a portion of the data that Chargaff collected.

Percentages of Bases in Five Organisms				
Source of DNA	**A**	**T**	**G**	**C**
Streptococcus	29.8	31.6	20.5	18.0
Yeast	31.3	32.9	18.7	17.1
Herring	27.8	27.5	22.2	22.6
Human	30.9	29.4	19.9	19.8
E.coli	24.7	23.6	26.0	25.7

1. Interpret Tables Which organism has the highest percentage of adenine?

2. Calculate If a species has 35 percent adenine in its DNA, what is the percentage of the other three bases? MATH

3. Draw Conclusions What did the fact that A and T, and G and C, occurred in equal amounts suggest about the relationship among these bases?

Rosalind Franklin

VISUAL SUMMARY

CLUES TO THE STRUCTURE OF DNA

FIGURE 12–6 Erwin Chargaff, Rosalind Franklin, James Watson, and Francis Crick were among the many scientists who helped solve the puzzle of DNA's molecular structure. Franklin's X-ray diffraction photograph shows the pattern that indicated the structure of DNA is helical.

Erwin Chargaff

Franklin's X-ray diffraction photograph, May 1952

BUILD Vocabulary

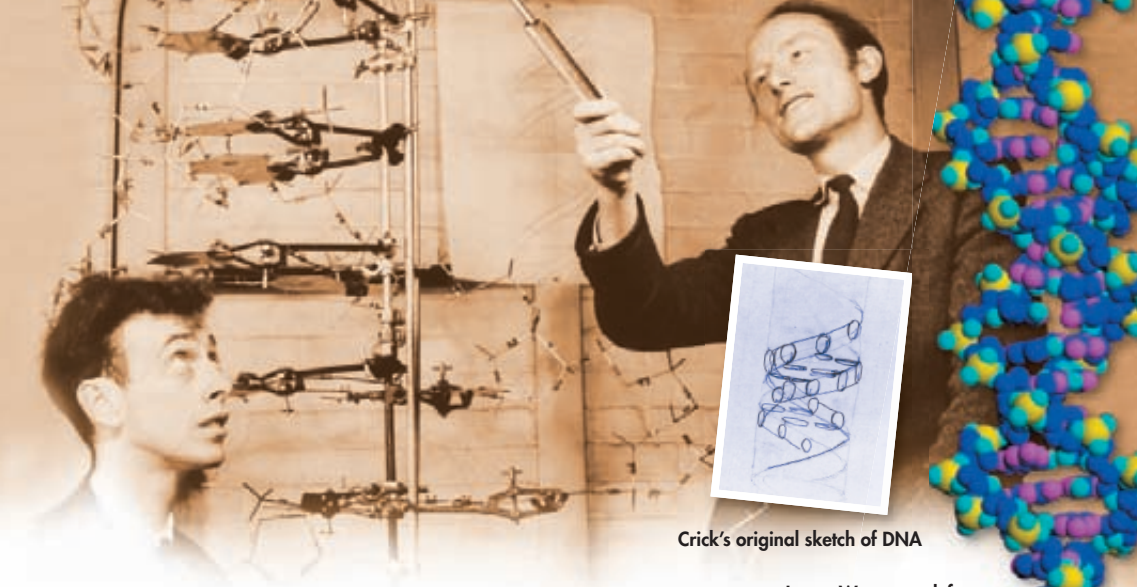
ACADEMIC WORDS In biochemistry, the noun **helix** refers to an extended spiral chain of units in a protein, nucleic acid, or other large molecule. The plural term is *helices*.

Franklin's X-Rays In the early 1950s, the British scientist Rosalind Franklin began to study DNA. Franklin used a technique called X-ray diffraction to get information about the structure of the DNA molecule. First, she purified a large amount of DNA, then stretched the DNA fibers in a thin glass tube so that most of the strands were parallel. Next, 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 obtain better and better patterns from DNA until the patterns became clear. The result of her work is the X-ray photograph shown in **Figure 12–6,** taken in the summer of 1952.

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 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 DNA molecule.

The Work of Watson and Crick While Franklin was continuing her research, James Watson, an American biologist, and Francis Crick, a British physicist, were also trying to understand the structure of DNA. They built three-dimensional models of the molecule that 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."



Crick's original sketch of DNA

James Watson, at left, and Francis Crick with their model of a DNA molecule in 1953

A computer model of DNA

The clues in Franklin's X-ray pattern enabled Watson and Crick to build a model that explained the specific structure and properties of DNA. The pair published their results in a historic one-page paper in April of 1953, when Franklin's paper describing her X-ray work was also published. Watson and Crick's breakthrough model of DNA was a double helix, in which two strands of nucleotide sequences were wound around each other.

The Double-Helix Model

What does the double-helix model tell us about DNA?

A double helix looks like a twisted ladder. In the double-helix model of DNA, the two strands twist around each other like spiral staircases. Watson and Crick realized that the double helix accounted for Franklin's X-ray pattern. Further still, it explained many of the most important properties of DNA. **The double-helix model explains Chargaff's rule of base pairing and how the two strands of DNA are held together.** This model can even tell us how DNA can function as a carrier of genetic information.

Antiparallel Strands One of the surprising aspects of the double-helix model is that the two strands of DNA run in opposite directions. In the language of biochemistry, these strands are "antiparallel." This arrangement enables the nitrogenous bases on both strands to come into contact at the center of the molecule. It also allows each strand of the double helix to carry a sequence of nucleotides, arranged almost like letters in a four-letter alphabet.

In Your Notebook *Draw and label your own model of the DNA double-helix structure.*

MYSTERY CLUE

Our skin cells are exposed to UV light whenever they are in direct sunlight. How might this exposure affect base pairing in the DNA of our skin cells?

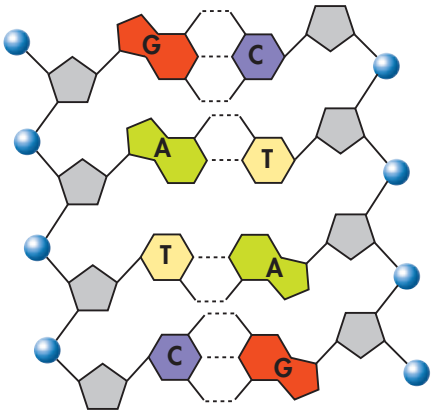


FIGURE 12–7 Base Pairing The two strands of DNA are held together by hydrogen bonds between the nitrogenous bases adenine and thymine, and between guanine and cytosine.

Hydrogen Bonding At first, Watson and Crick could not explain what forces held the two strands of DNA's double helix together. They then discovered that hydrogen bonds could form between certain nitrogenous bases, providing just enough force to hold the two strands together. As you may recall, hydrogen bonds are relatively weak chemical forces.

Does it make sense that a molecule as important as DNA should be held together by weak bonds? Indeed, it does. If the two strands of the helix were held together by strong bonds, it might well be impossible to separate them. As we will see, the ability of the two strands to separate is critical to DNA's functions.

Base Pairing Watson and Crick's model showed that hydrogen bonds could create a nearly perfect fit between nitrogenous bases along the center of the molecule. However, these bonds would form only between certain base pairs—adenine with thymine, and guanine with cytosine. This nearly perfect fit between A–T and G–C nucleotides is known as **base pairing,** and is illustrated in **Figure 12–7.**

Once they observed this process, Watson and Crick realized that base pairing explained Chargaff's rule. It gave a reason why [A] = [T] and [G] = [C]. For every adenine in a double-stranded DNA molecule, there has to be exactly one thymine. For each cytosine, there is one guanine. The ability of their model to explain Chargaff's observations increased Watson and Crick's confidence that they had come to the right conclusion, with the help of Rosalind Franklin.

12.2 Assessment

Review Key Concepts

1. a. Review List the chemical components of DNA.

b. Relate Cause and Effect Why are hydrogen bonds so essential to the structure of DNA?

2. a. Review Describe the discoveries that led to the modeling of DNA.

b. Infer Why did scientists have to use tools other than microscopes to solve the structure of DNA?

3. a. Review Describe Watson and Crick's model of the DNA molecule.

b. Apply Concepts Did Watson and Crick's model account for the equal amounts of thymine and adenine in DNA? Explain.

VISUAL THINKING

4. Make a three-dimensional model showing the structure of a DNA molecule. Your model should include the four base pairs that help form the double helix.

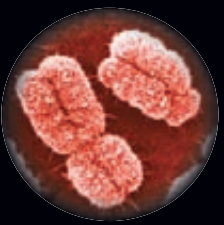
BIOLOGY.com Search Lesson 12.2 GO • Self-Test • Lesson Assessment

Biology & HISTORY

Discovering the Role of DNA **Genes and the principles of genetics 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.**

1860 1880 1900 1920 1940 1960 1980 2000

1865
Gregor Mendel shows that the characteristics of pea plants are passed along in a predictable way. His discovery begins the science of genetics.



1903
◄ **Walter Sutton** shows that chromosomes carry the cell's units of inheritance.

1911
Thomas Hunt Morgan ▲ demonstrates that genes are arranged in linear fashion on the chromosomes of the fruit fly.

1928
▼ **Frederick Griffith** discovers that bacteria contain a molecule that can transfer genetic information from cell to cell.

1944
Oswald Avery, Colin Macleod, and Maclyn McCarty show the substance that Griffith discovered is DNA.

1950
Erwin Chargaff analyzes the base composition of DNA in cells. He discovers that the amounts of adenine and thymine are almost always equal, as are the amounts of guanine and cytosine.

1952
Alfred Hershey and Martha Chase confirm that the genetic material of viruses is DNA, not protein. **Rosalind Franklin** records a critical X-ray diffraction pattern, demonstrating that DNA is in the form of a helix.

1953
James Watson and Francis Crick publish their model of the DNA double helix. The model was made possible by Franklin's work.

2000
▼ **Craig Venter and Francis Collins** announce the draft DNA sequence of the human genome at a White House ceremony in Washington, D.C. The final version is published in 2003.

WRITING **Use library or Internet resources to find out what James Watson or Francis Crick worked on after discovering the structure of DNA. Organize your findings about the scientist's work and make a multimedia presentation for the class.**

12.3 DNA Replication

Key Questions

What role does DNA polymerase play in copying DNA?

How does DNA replication differ in prokaryotic cells and eukaryotic cells?

Vocabulary

replication
DNA polymerase
telomere

Taking Notes

Preview Visuals Before you read, study the diagram in **Figure 12–8.** Make a list of questions about the diagram. As you read, write down the answers to your questions.

BUILD Vocabulary

WORD ORIGINS The prefix *re-* means "back" or "again." *Plicare* is a Latin verb meaning "to fold." To replicate something is, in a sense, to repeat it, or to fold back again.

THINK ABOUT IT Before a cell divides, its DNA must first be copied. How might the double-helix structure of DNA make that possible? What might happen if one of the nucleotides were damaged or chemically altered just before the copying process? How might this affect the DNA inherited by each daughter cell after cell division?

Copying the Code

What role does DNA polymerase play in copying DNA?

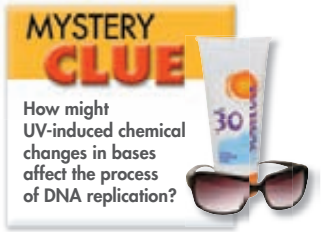
When Watson and Crick discovered the structure of DNA, they immediately recognized one genuinely surprising aspect of the structure. Base pairing in the double helix explains how DNA can be copied, or replicated, because each base on one strand pairs with one—and only one—base on the opposite strand. Each strand of the double helix therefore 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.

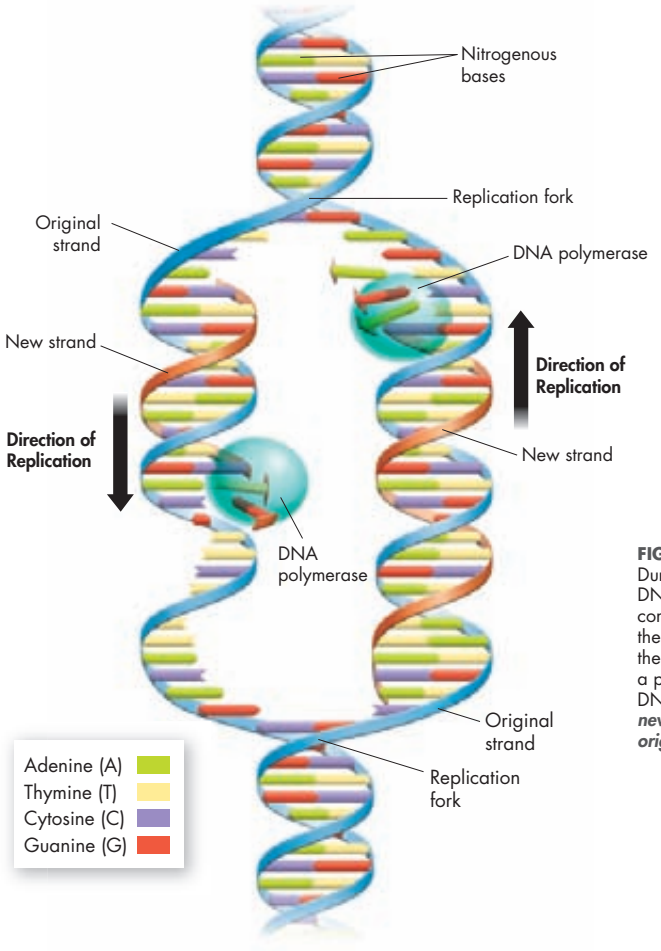
The Replication Process Before a cell divides, it duplicates its DNA in a copying process called **replication.** This process, which occurs during late interphase of the cell cycle, ensures that each resulting cell has the same complete set of DNA molecules. During replication, the DNA molecule separates 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 12–8 shows the process of DNA replication. The two strands of the double helix have separated, or "unzipped," allowing two replication forks to form. As each new strand forms, new bases are added following the rules of base pairing. If the base on the old strand is adenine, then thymine is added to the newly forming strand. Likewise, guanine is always paired to cytosine. For example, a strand that has the base sequence TACGTT produces a strand with the complementary base sequence 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.

In Your Notebook *In your own words, describe the process of DNA replication.*

The Role of Enzymes DNA replication is carried out by a series of enzymes. These enzymes first "unzip" a molecule of DNA by breaking the hydrogen bonds between base pairs and unwinding the two strands of the molecule. Each strand then serves as a template for the attachment of complementary bases. You may recall that enzymes are proteins with highly specific functions. 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). **DNA polymerase is an enzyme that joins individual nucleotides to produce a new strand of DNA.** Besides producing the sugar-phosphate bonds that join nucleotides together, DNA polymerase also "proofreads" each new DNA strand, so that each molecule is a near-perfect copy of the original.





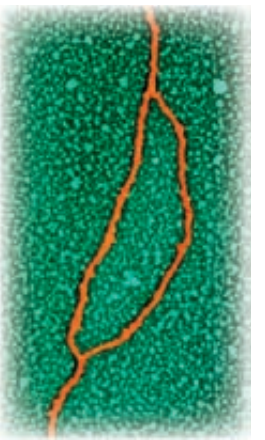


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FIGURE 12–8 DNA Replication During DNA replication, the DNA molecule produces two new complementary strands. Each strand of the double helix serves as a template for the new strand. The micrograph shows a pair of replication forks in human DNA. **Apply Concepts** ***What makes the new DNA strand complementary to the original strand?***

Quick Lab
OPEN-ENDED INQUIRY

Modeling DNA Replication

❶ Cut out small squares of white and yellow paper to represent phosphate and sugar molecules. Then, cut out small strips of blue, green, red, and orange paper to represent the four nitrogenous bases. Build a set of five nucleotides using your paper strips and tape. Look back at **Figure 12–5** if you need help.

❷ Using your nucleotides, tape together a single strand of DNA. Exchange strands with a partner.

❸ Model DNA replication by creating a strand that is complementary to your partner's original strand.

Analyze and Conclude

1. **Use Models** Taping together the nucleotides models the action of what enzyme?
2. **Evaluate** In what ways does this lab accurately represent DNA replication? How could you improve the lab to better show the steps of replication?

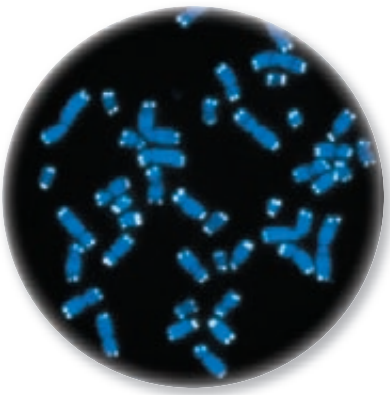

FIGURE 12–9 Telomeres The telomeres are the white (stained) part of the blue human chromosomes.

Telomeres DNA at the tips of chromosomes are known as **telomeres** (**Figure 12–9**). This DNA is particularly difficult to replicate. Cells use a special enzyme, called telomerase, to solve this problem by adding short, repeated DNA sequences to the telomeres. In rapidly dividing cells, such as stem cells and embryonic cells, telomerase helps to prevent genes from being damaged or lost during replication. Telomerase is often switched off in adult cells. In cancer cells, however, telomerase may be activated, enabling these cells to grow and proliferate rapidly.

Replication in Living Cells

How does DNA replication differ in prokaryotic cells and eukaryotic cells?

DNA replication occurs during the S phase of the cell cycle. As we saw in Chapter 10, replication is carefully regulated, along with the other critical events of the cycle so that it is completed before a cell enters mitosis or meiosis. But where, exactly, is DNA found inside a living cell?

The cells of most prokaryotes have a single, circular DNA molecule in the cytoplasm, containing nearly all the cell's genetic information. Eukaryotic cells, on the other hand, can have up to 1000 times more DNA. Nearly all of the DNA of eukaryotic cells is found in the nucleus, packaged into chromosomes. Eukaryotic chromosomes consist of DNA, tightly packed together with proteins to form a substance called chromatin. Together, the DNA and histone molecules form beadlike structures called nucleosomes, as described in Chapter 10. Histones, you may recall, are proteins around which chromatin is tightly coiled.

Prokaryotic DNA Replication In most prokaryotes, DNA replication does not start until regulatory proteins bind to a single starting point on the chromosome. These proteins then trigger the beginning of the S phase, and DNA replication begins. **Replication in most prokaryotic cells starts from a single point and proceeds in two directions until the entire chromosome is copied.** This process is shown in **Figure 12–10.** Often, the two chromosomes produced by replication are attached to different points inside the cell membrane and are separated when the cell splits to form two new cells.

Eukaryotic DNA Replication Eukaryotic chromosomes are generally much bigger than those of prokaryotes. **In eukaryotic cells, replication may begin at dozens or even hundreds of places on the DNA molecule, proceeding in both directions until each chromosome is completely copied.** Although a number of proteins check DNA for chemical damage or base pair mismatches prior to replication, the system is not foolproof. Damaged regions of DNA are sometimes replicated, resulting in changes to DNA base sequences that may alter certain genes and produce serious consequences.

The two copies of DNA produced by replication in each chromosome remain closely associated until the cell enters prophase of mitosis. At that point, the chromosomes condense, and the two chromatids in each chromosome become clearly visible. They separate from each other in anaphase of mitosis, as described in Chapter 10, producing two cells, each with a complete set of genes coded in DNA.

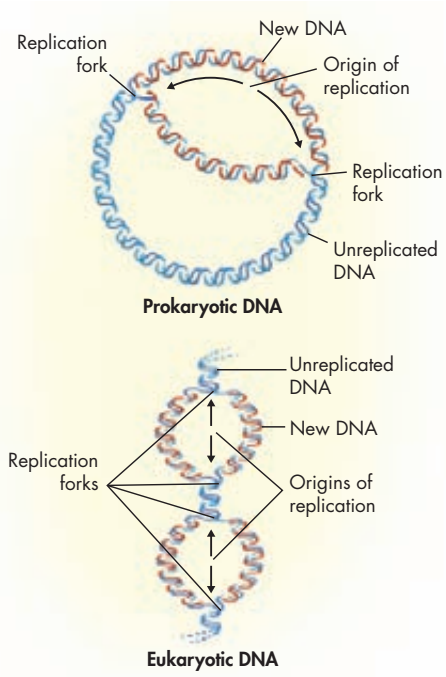

FIGURE 12–10 Differences in DNA Replication Replication in most prokaryotic cells (top) begins at a single starting point and proceeds in two directions until the entire chromosome is copied. In eukaryotic cells (bottom), replication proceeds from multiple starting points on individual chromosomes and ends when all the chromosomes are copied.

12.3 Assessment

Review Key Concepts

1. a. Review How is DNA replicated?

b. Apply Concepts What is the role of DNA polymerase in DNA replication?

2. a. Review Where and in what form is prokaryotic DNA found? Where is eukaryotic DNA found?

b. Infer What could be the result of damaged DNA being replicated?

VISUAL THINKING

3. 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.

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Pre-Lab: Extracting DNA

Problem What properties of DNA can you observe when you extract DNA from cells?

Materials self-sealing plastic freezer bag, ripe strawberry, detergent solution, 25-mL graduated cylinder, cheesecloth, funnel, test tube, test tube rack, chilled ethanol, stirring rod

Lab Manual Chapter 12 Lab

Skills Focus Predict, Observe, Draw Conclusions

Connect to the Big idea Not surprisingly, the molecules that store genetic information are long molecules. If the DNA from a human cell were unfolded, the double helix structure would be about one meter long. Yet, most of a cell's DNA can be folded and tightly packed inside the cell's tiny nucleus. How can scientists remove DNA from the nucleus so that it can be studied and analyzed? In this lab, you will learn that extracting DNA from living tissue is not as difficult as you might think.

Background Questions

a. Review Describe the structure of a DNA molecule.

b. Review What type of bond holds the strands of DNA together?

c. Apply Concepts How does the strength of those bonds affect how DNA functions?

Pre-Lab Questions

Preview the procedure in the lab manual.

1. Apply Concepts Why do strawberry cells need DNA?

2. Form a Hypothesis If you observe a cell nucleus under a compound microscope, you will not see a molecule of DNA. Why will you be able to see the DNA you extract?

3. Predict Use what you know about DNA to predict some of the physical properties of DNA.

4. Design an Experiment How could you determine what percentage of a strawberry's mass is DNA?

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Visit Chapter 12 online to test yourself on chapter content and to find activities to help you learn.

Untamed Science Video The Untamed Science CSI crew unravels the secrets of DNA left at the scene of a crime.

Art in Motion View an animation that re-creates the Hershey-Chase experiments.

Art Review Review your understanding of both prokaryotic and eukaryotic DNA replication.

InterActive Art Drag-and-drop base pairs to build your own strand of DNA while you practice the process of DNA replication.

Data Analysis Learn how analysis of DNA base sequences can be used to track animal poaching.

Tutor Tube Tune into the tutor to find out hints for remembering which bases pair together.

Visual Analogy Compare transcription and translation with the process of publishing a book.

12 Study Guide

Big ideas Information and Heredity, Cellular Basis of Life

DNA is a double-stranded protein molecule made up of nucleotide base pairs. DNA stores, copies, and transmits the genetic information in a cell.

12.1 Identifying the Substance of Genes

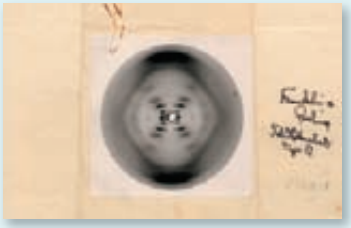
- By observing bacterial transformation, Avery and other scientists discovered that the nucleic acid DNA stores and transmits genetic information from one generation of bacteria to the next.
- Hershey and Chase's experiment with bacteriophages confirmed Avery's results, convincing many scientists that DNA was the genetic material found in genes—not just in viruses and bacteria, but in all living cells.
- The DNA that makes up genes must be capable of storing, copying, and transmitting the genetic information in a cell.

transformation (339) bacteriophage (340)

12.2 The Structure of DNA

- DNA is a nucleic acid made up of nucleotides joined into long strands or chains by covalent bonds.
- The clues in Franklin's X-ray pattern enabled Watson and Crick to build a model that explained the specific structure and properties of DNA.
- The double-helix model explains Chargaff's rule of base pairing and how the two strands of DNA are held together.

base pairing (348)

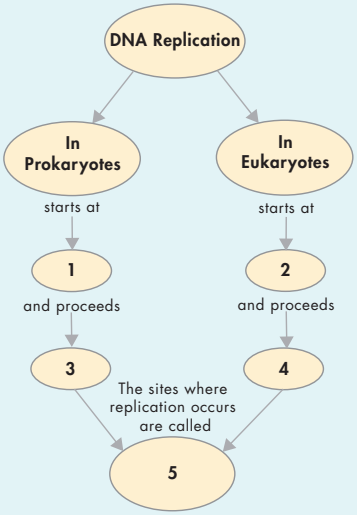


12.3 DNA Replication

- DNA polymerase is an enzyme that joins individual nucleotides to produce a new strand of DNA.
- Replication in most prokaryotic cells starts from a single point and proceeds in two directions until the entire chromosome is copied.
- In eukaryotic cells, replication may begin at dozens or even hundreds of places on the DNA molecule, proceeding in both directions until each chromosome is completely copied.

replication (350) telomere (352)
DNA polymerase (351)

Think Visually Using the information in this chapter, complete the following concept map about DNA replication:



12 Assessment

12.1 Identifying the Substance of Genes

Understand Key Concepts

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

2. Bacteriophages are
   a. a form of bacteria. **c.** coils of DNA.
   b. enzymes. **d.** viruses.

3. Which of the following researchers used radioactive markers in experiments to show that DNA was the genetic material in cells?
   a. Frederick Griffith
   b. Oswald Avery
   c. Alfred Hershey and Martha Chase
   d. James Watson and Francis Crick

4. Before DNA could definitively be shown to be the genetic material in cells, scientists had to show that it could
   a. tolerate high temperatures.
   b. carry and make copies of information.
   c. be modified in response to environmental conditions.
   d. be broken down into small subunits.

5. Briefly describe the conclusion that could be drawn from the experiments of Frederick Griffith.

6. What was the key factor that allowed Hershey and Chase to show that DNA alone carried the genetic information of a bacteriophage?

Think Critically

7. **Interpret Visuals** Look back at Griffith's experiment shown in **Figure 12–1.** Describe the occasion in which the bacterial DNA withstood conditions that killed the bacteria. What happened to the DNA during the rest of the experiment?

8. **Evaluate** Avery and his team identified DNA as the molecule responsible for the transformation seen in Griffith's experiment. How did they control variables in their experiment to make sure that only DNA caused the effect?

12.2 The Structure of DNA

Understand Key Concepts

9. A nucleotide does NOT contain
   a. a 5-carbon sugar.
   b. an amino acid.
   c. a nitrogen base.
   d. a phosphate group.

10. According to Chargaff's rule of base pairing, which of the following is true about DNA?
    a. A = T, and C = G
    b. A = C, and T = G
    c. A = G, and T = C
    d. A = T = C = G

11. The bonds that hold the two strands of DNA together come from
    a. the attraction of phosphate groups for each other.
    b. strong bonds between nitrogenous bases and the sugar-phosphate backbone.
    c. weak hydrogen bonds between nitrogenous bases.
    d. carbon-to-carbon bonds in the sugar portion of the nucleotides.

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

13. Explain how Chargaff's rule of base pairing helped Watson and Crick model DNA.

14. What important clue from Rosalind Franklin's work helped Watson and Crick develop their model of DNA?

15. Why is it significant that the two strands of DNA are antiparallel?

Think Critically

16. **Use Models** How did Watson and Crick's model of the DNA molecule explain base pairing?

17. **Infer** Rosalind Franklin's X-ray pattern 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 bases are paired?

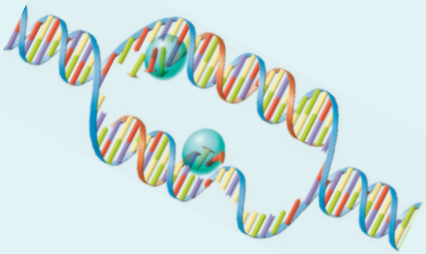
12.3 DNA Replication

Understand Key Concepts

18. In prokaryotes, DNA molecules are located in the
a. nucleus. **c.** cytoplasm.
b. ribosomes. **d.** histones.

19. In eukaryotes, nearly all the DNA is found in the
a. nucleus. **c.** cytoplasm.
b. ribosomes. **d.** histones.

20. The diagram below shows the process of DNA
a. replication. **c.** transformation.
b. digestion. **d.** transpiration.



21. The main enzyme involved in linking individual nucleotides into DNA molecules is
a. DNA protease. **c.** carbohydrase.
b. ribose. **d.** DNA polymerase.

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

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

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

Think Critically

25. **Use 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.

26. **Compare and Contrast** Describe the similarities and differences between DNA replication in prokaryotic cells and in eukaryotic cells.

solve the CHAPTER MYSTERY

UV LIGHT

The nucleotides in DNA include the nitrogenous bases adenine, cytosine, guanine, and thymine (A, C, G, and T). The energy from UV light can produce chemical changes in these bases, damaging the DNA molecule and producing errors when DNA is replicated.

1. **Predict** Use your understanding of the structure of DNA to predict what sorts of problems excessive UV light might produce in the DNA molecule. How might these changes affect the functions of DNA?

2. **Infer** All cells have systems of enzymes that repair UV-induced damage to their DNA. Some cellular systems block DNA replication if there are base pairing problems in the double helix. Why are these systems important? How might they work?

3. **Relate Cause and Effect** Analyze the effects that UV light might have on skin cells. Why is UV light so dangerous? Why is the skin particularly vulnerable to it?

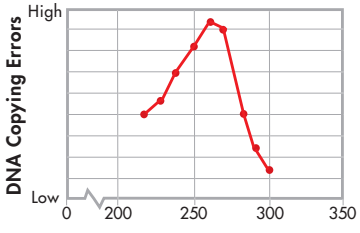
4. **Connect to the Big idea** Among humans who inherit genetic defects in their DNA-repair systems, the incidence of skin cancer is as much as 1000 times greater than average. Based on this information, what can you infer about the effect of UV light on DNA?

Connecting Concepts

Use Science Graphics

A scientist studied the effect of exposing DNA to various wavelengths of ultraviolet light. The scientist determined the number of copying errors made after exposure to ultraviolet rays. The graph shows the results. Use the graph to answer questions 27 and 28.

DNA Replication Errors



27. Interpret Graphs The most damaging effects of ultraviolet light on DNA replication occur at which wavelength?

28. Infer What conclusion would you draw from the graph about the effect of ultraviolet light on living organisms?

29. Pose Questions Ozone is a molecule that is very effective at absorbing ultraviolet light from the sun. Evidence indicates that human activities have contributed to the destruction of ozone in the atmosphere. What question would you ask about the effect of removing ozone from the atmosphere?

Write About Science

30. Explanation Recall that Gregor Mendel concluded that factors, which we now call genes, determine the traits that pass from one generation to the next. Imagine that you could send a letter backward in time to Mendel. Write a letter to him in which you explain what a gene consists of in molecular terms.

31. Assess the Big idea In their original paper describing the structure of DNA, Watson and Crick noted in a famous sentence that the structure they were proposing immediately suggested how DNA could make a copy of itself. Explain what Watson and Crick meant when they said this.

Analyzing Data

The following table shows the results of measuring the percentages of the four bases in the DNA of several different organisms. Some of the values are missing from the table.

Nitrogenous Bases (%)

Organism	A	G	T	C
Human		19.9	29.4	
Chicken	28.8			21.5
Bacterium (*S. lutea*)	13.4			

32. Predict Based on Chargaff's rule, the percentage of adenine bases in human DNA should be around

a. 30.9%. **c.** 21.5%.
b. 19.9%. **d.** 13.4%.

33. Calculate The value for the percent of guanine bases in the bacterium would be expected to be about MATH

a. 13.4%.
b. 28.8%.
c. 36.6%.
d. There is not enough information given.

34. Predict If the two DNA strands of the bacterium were separated and the base composition of just one of the strands was determined, you could expect

a. the amount of A to equal the amount of T.
b. the amount of C to equal the amount of G.
c. the amount of A to equal the amounts of T, C, and G.
d. the four nitrogenous bases to have any value.

Standardized Test Prep

Multiple Choice

1. During replication, which sequence of nucleotides would bond with the DNA sequence TATGA?
A TATGA **C** CACTA
B ATACT **D** AGTAT

2. The scientist(s) responsible for the discovery of bacterial transformation is (are)
A Watson and Crick. **C** Griffith.
B Avery. **D** Franklin.

3. Which of the following does NOT describe the structure of DNA?
A double helix
B nucleotide polymer
C contains adenine-guanine pairs
D sugar-phosphate backbone

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

5. The two "backbones" of the DNA molecule consist of
A adenines and sugars.
B phosphates and sugars.
C adenines and thymines.
D thymines and sugars.

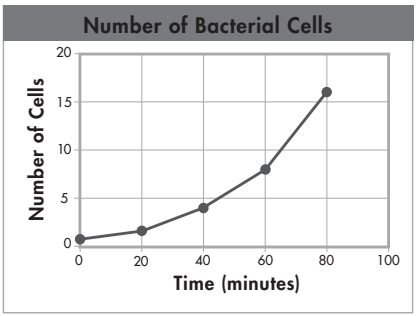
6. In eukaryotic chromosomes, DNA is tightly coiled around proteins called
A DNA polymerase.
B chromatin.
C histones.
D nucleotides.

7. When prokaryotic cells copy their DNA, replication begins at
A one point on the DNA molecule.
B two points on opposite ends of the DNA molecule.
C dozens to hundreds of points along the molecule.
D opposite ends of the molecule.

8. Compared to eukaryotic cells, prokaryotic cells contain
A about 1000 times more DNA.
B about one thousandth as much DNA.
C twice as much DNA.
D the same amount of DNA.

Questions 9–10

Under ideal conditions, a single bacterial cell can reproduce every 20 minutes. The graph shows how the total number of cells under ideal conditions can change over time.



9. How many cells are present after 80 minutes?
A 1 **C** 16
B 2 **D** 32

10. If the DNA of this bacterium is 4 million base pairs in length, how many total molecules of A, T, C, and G are required for replication to be successful?
A 2 million
B 4 million
C 8 million
D 32 million

Open-Ended Response

11. Describe how eukaryotic cells are able to keep such large amounts of DNA in the small volume of the cell nucleus.

If You Have Trouble With . . .											
Question	1	2	3	4	5	6	7	8	9	10	11
See Lesson	12.3	12.1	12.2	12.1	12.2	12.3	12.3	12.3	12.3	12.3	12.3