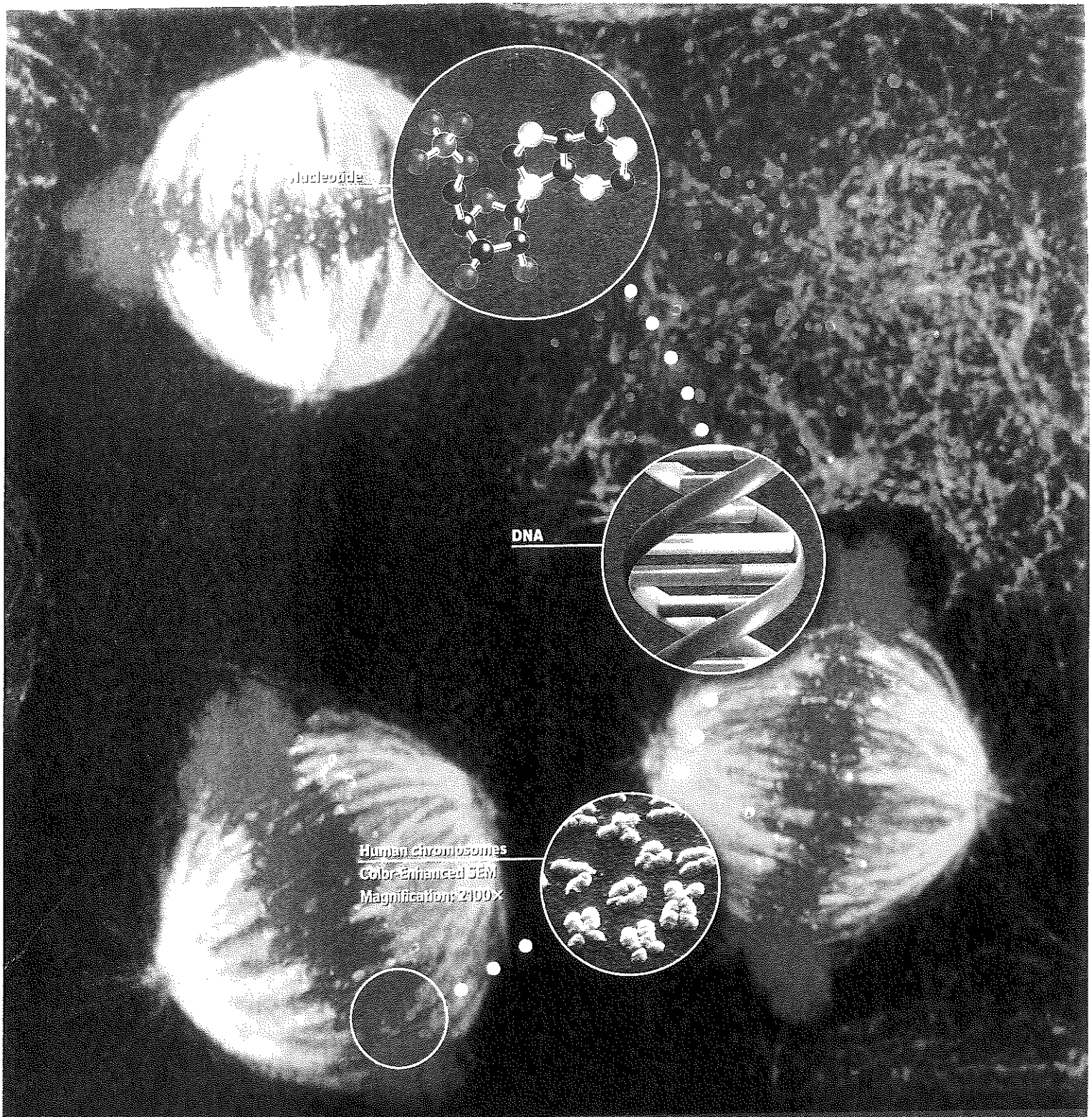


THEME FOCUS **Stability and Change**
Mutations within DNA can be passed on to future generations.

DNA is the genetic material that contains a code for proteins.

Section 1 • DNA: The Genetic Material

Section 2 • Replication of DNA

Section 3 • DNA, RNA, and Protein

Section 4 • Gene Regulation and Mutation

Reading Preview

Essential Questions

- Which experiments led to the discovery of DNA as the genetic material?
- What is the basic structure of DNA?
- What is the basic structure of eukaryotic chromosomes?

Review Vocabulary

nucleic acid: complex biomolecule that stores cellular information in the form of a code

New Vocabulary

double helix
nucleosome

Multilingual eGlossary

DNA: The Genetic Material

Key Idea The discovery that DNA is the genetic code involved many experiments.

Real-World Reading Link Do you like to read mystery novels or watch people on television solve crimes? Detectives search for clues that will help them solve the mystery. Geneticists are detectives looking for clues in the mystery of inheritance.

Discovery of the Genetic Material

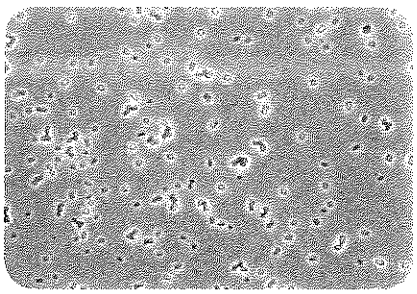
Once Mendel's work was rediscovered in the 1900s, scientists began to search for the molecule involved in inheritance. Scientists knew that genetic information was carried on the chromosomes in eukaryotic cells, and that the two main components of chromosomes are DNA and protein. For many years, scientists tried to determine which of these macromolecules–nucleic acid (DNA) or proteins–was the source of genetic information.

Griffith The first major experiment that led to the discovery of DNA as the genetic material was performed by Frederick Griffith in 1928. Griffith studied two strains of the bacteria *Streptococcus pneumoniae,* which causes pneumonia. He found that one strain could be transformed, or changed, into the other form.

Of the two strains he studied, one had a sugar coat and one did not. Both strains are shown in **Figure 1.** The coated strain causes pneumonia and is called the smooth (S) strain. The noncoated strain does not cause pneumonia and is called the rough (R) strain because, without the coat, the bacteria colonies have rough edges.

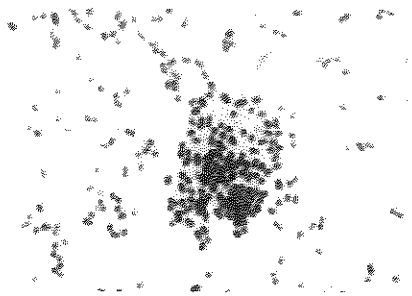
Follow Griffith's study described in **Figure 2.** Notice the live S cells killed the mouse in the study. The live R cells did not kill the mouse, and the killed S cells did not kill the mouse. However, when Griffith made a mixture of live R cells and killed S cells and injected the mixture into a mouse, the mouse died. Griffith isolated live bacteria from the dead mouse. When these isolated bacteria were cultured, the smooth trait was visible, suggesting that a disease-causing factor was passed from the killed S bacteria to the live R bacteria. Griffith concluded that there had been a transformation from live R bacteria to live S bacteria. This experiment set the stage for the search to identify the transforming substance.

SEM Magnification: 320×



Smooth strain—*S. pneumoniae*

SEM Magnification: 800×



Rough strain—*S. pneumoniae*

Michael Abbey/Photo Researchers

Figure 1 The smooth (S) strain of *S. pneumoniae* can cause pneumonia, though the rough (R) strain is not disease-causing. The strains can be identified by the appearance of the colonies.

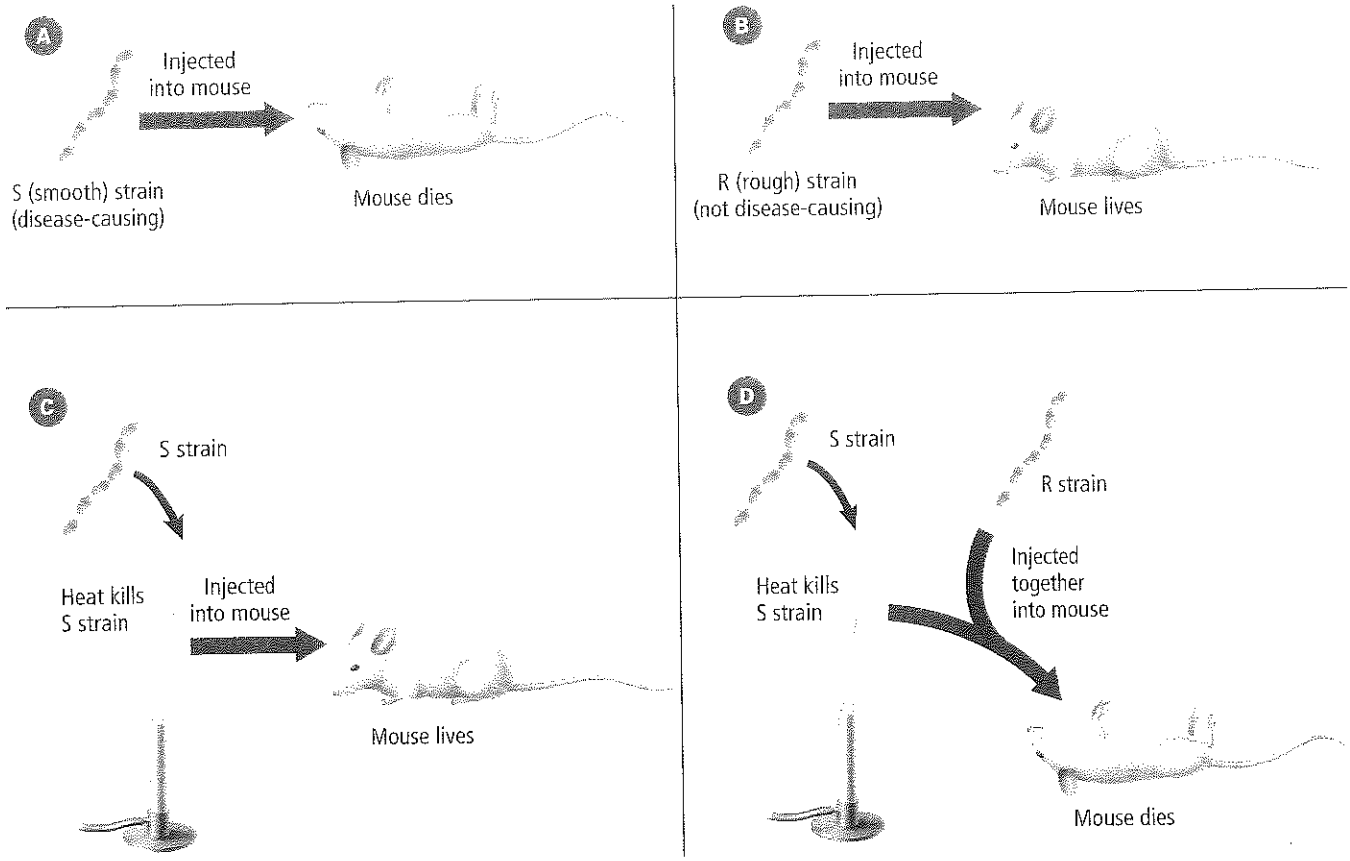


Figure 2 Griffith's transformation experiment demonstrates the change of rough bacteria into smooth bacteria.
***Explain** why Griffith concluded there had been a change from live R bacteria to live S bacteria.*

Avery In 1944, Oswald Avery and his colleagues identified the molecule that transformed the R strain of bacteria into the S strain. Avery isolated different macromolecules, such as DNA, proteins, and lipids, from killed S cells. Then he exposed live R cells to the macromolecules separately. When the live R cells were exposed to the S strain DNA, they were transformed into S cells. Avery concluded that when the S cells in Griffith's experiments were killed, DNA was released. Some of the R bacteria incorporated this DNA into their cells, and this changed the bacteria into S cells. Avery's conclusions were not widely accepted by the scientific community, and many biologists continued to question and experiment to determine whether proteins or DNA were responsible for the transfer of genetic material.

Reading Check **Explain** how Avery discovered the transforming factor.

Hershey and Chase In 1952, Alfred Hershey and Martha Chase published results of experiments that provided definitive evidence that DNA was the transforming factor. These experiments involved a bacteriophage (bak TIHR ee uh fayj), a type of virus that attacks bacteria. Two components made the experiment ideal for confirming that DNA is the genetic material. First, the bacteriophage used in the experiment was made of DNA and protein. Second, viruses cannot replicate themselves. They must inject their genetic material into a living cell to reproduce. Hershey and Chase labeled both parts of the virus to determine which part was injected into the bacteria and, thus, which part was the genetic material.

Vocabulary
Academic Vocabulary
Transform
to cause a change in type or kind
Avery used DNA to transform bacteria.

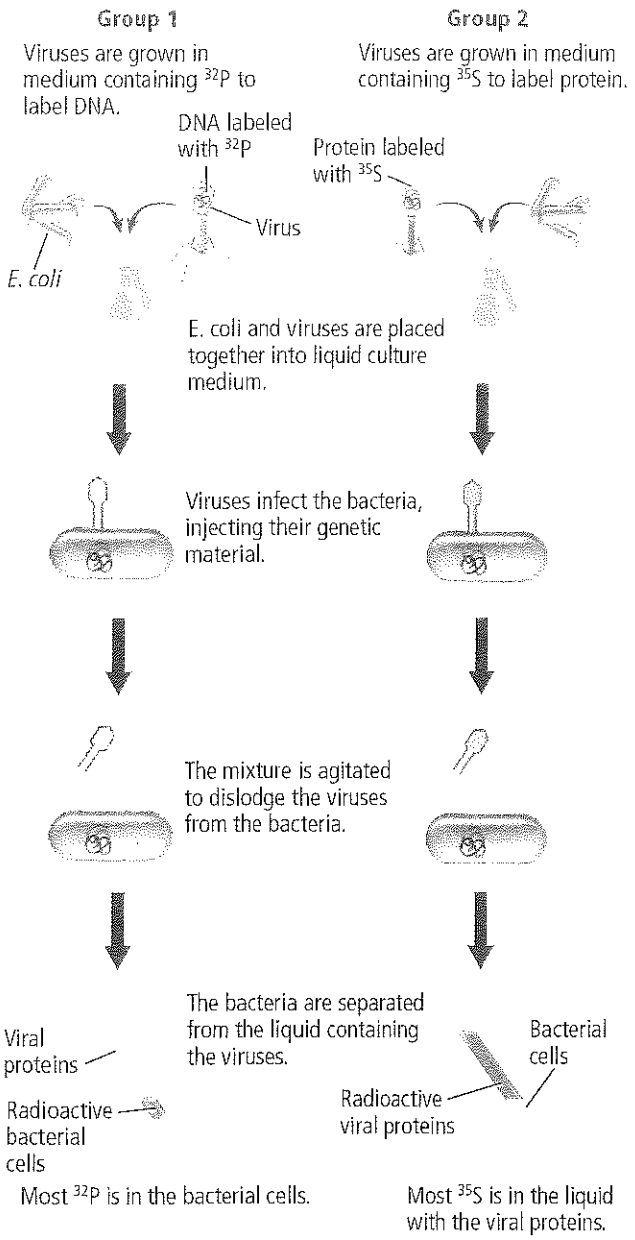


Figure 3 Hershey and Chase used radioactive labeling techniques to demonstrate that DNA is the genetic material in viruses.

Radioactive labeling Hershey and Chase used a technique called radioactive labeling to trace the fate of the DNA and protein as the bacteriophages infected bacteria and reproduced. Follow along in **Figure 3** as you continue learning about the Hershey-Chase experiment. They labeled one set of bacteriophages with radioactive phosphorus (^{32}P). Proteins do not contain phosphorous, so DNA and not protein in these viruses would be radioactive. Hershey and Chase labeled another set of bacteriophages with radioactive sulfur (^{35}S). Because proteins contain sulfur and DNA does not, proteins and not DNA would be radioactive.

Hershey and Chase infected bacteria with viruses from the two groups. When viruses infect bacteria, they attach to the outside of the bacteria and inject their genetic material. The infected bacteria then were separated from the viruses.

Tracking DNA Hershey and Chase examined Group 1 labeled with ^{32}P and found that the labeled viral DNA had been injected into the bacteria. Viruses later released from the infected bacteria contained ^{32}P, further indicating that DNA was the carrier of genetic information.

When examining Group 2 labeled with ^{35}S, Hershey and Chase observed that the labeled proteins were found outside of the bacterial cells. Viral replication had occurred in the bacterial cells, indicating that the viruses' genetic material had entered the bacteria, but no label (^{35}S) was found. **Table 1** summarizes the results of the Hershey-Chase experiment.

Based on their results, Hershey and Chase concluded that the viral DNA was injected into the cell and provided the genetic information needed to produce new viruses. This experiment provided powerful evidence that DNA, not protein, was the genetic material that could be passed from generation to generation in viruses.

Reading Check **Explain** why it is important that new viruses were produced in the bacteria.

Table 1 Summary of Hershey-Chase Results

Interactive Table

Group 1 (Viruses labeled with ^{32}P)		Group 2 (Viruses labeled with ^{35}S)	
Infected Bacteria	**Liquid with Viruses**	**Infected Bacteria**	**Liquid with Viruses**
• Labeled viral DNA (^{32}P) found in the bacteria • Viral replication occurred • New viruses contained ^{32}P	• No labeled DNA • No viral replication	• No labeled viral proteins (^{35}S) • Viral replication occurred • New viruses did not have a label	• Labeled proteins found • No viral replication

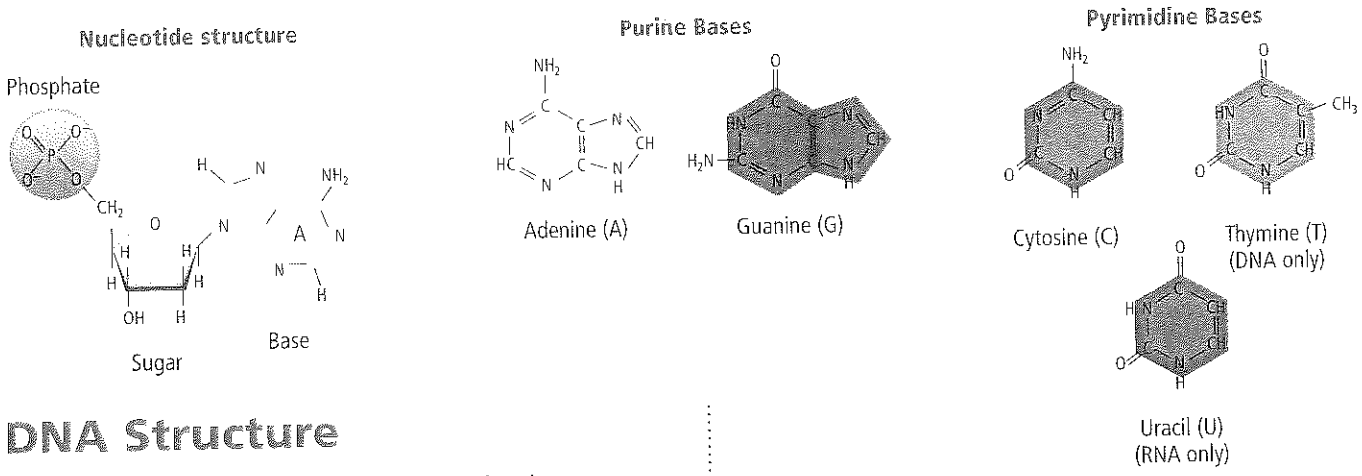


Figure 4 Nucleotides are made of a phosphate, sugar, and a base. There are five different bases found in nucleotide subunits that make up DNA and RNA.
Identify the structural difference between purine and pyrimidine bases.

DNA Structure

After the Hershey-Chase experiment, scientists were more confident that DNA was the genetic material. The clues had led to the identification of the genetic material, but the questions of how nucleotides came together to form DNA and how DNA could communicate information remained.

Nucleotides In the 1920s, the biochemist P. A. Levene determined the basic structure of nucleotides that make up DNA. Nucleotides are the subunits of nucleic acids and consist of a five-carbon sugar, a phosphate group, and a nitrogenous base. The two nucleic acids found in living cells are DNA and RNA. DNA nucleotides contain the sugar deoxyribose (dee ahk sih RI bos), a phosphate, and one of four nitrogenous bases: adenine (A duh neen), guanine (GWAH neen), cytosine (SI tuh seen), or thymine (THI meen). RNA nucleotides contain the sugar ribose, a phosphate, and one of four nitrogenous bases: adenine, guanine, cytosine, or uracil (YOO ruh sihl). Notice in **Figure 4** that guanine (G) and adenine (A) are double-ringed bases. This type of base is called a purine base. Thymine (T), cytosine (C), and uracil (U) are single-ringed bases called pyrimidine bases.

Chargaff Erwin Chargaff analyzed the amount of adenine, guanine, thymine, and cytosine in the DNA of various species. A portion of Chargaff's data, published in 1950, is shown in **Figure 5.** Chargaff found that the amount of guanine nearly equals the amount of cytosine, and the amount of adenine nearly equals the amount of thymine within a species. This finding is known as Chargaff's rule: C = G and T = A.

The structure question When four scientists joined the search for the DNA structure, the meaning and importance of Chargaff's data became clear. Rosalind Franklin, a British chemist; Maurice Wilkins, a British physicist; Francis Crick, a British physicist; and James Watson, an American biologist, provided information that was pivotal in answering the DNA structure question.

Figure 5 Chargaff's data showed that though base composition varies from species to species, within a species C = G and A = T.

Chargaff's Data

	Base Composition (Mole Percent)			
Organism	A	T	G	C
Escherichia coli	26.0	23.9	24.9	25.2
Yeast	31.3	32.9	18.7	17.1
Herring	27.8	27.5	22.2	22.6
Rat	28.6	28.4	21.4	21.5
Human	30.9	29.4	19.9	19.8

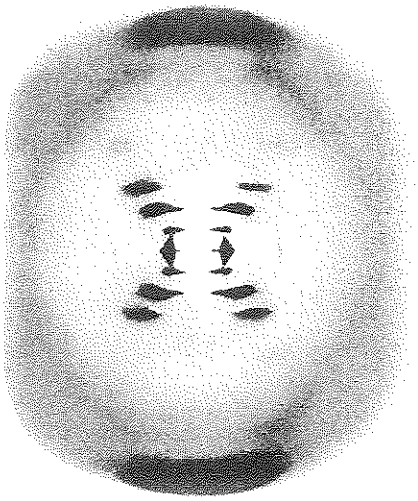


Figure 6 Rosalind Franklin's Photo 51 and X-ray diffraction data helped Watson and Crick solve the structure of DNA. When analyzed and measured carefully, the pattern shows the characteristics of helix structure.

X-ray diffraction Wilkins was working at King's College in London, England, with a technique called X-ray diffraction, a technique that involved aiming X rays at the DNA molecule. In 1951, Franklin joined the staff at King's College. There she took the now famous Photo 51 and collected data eventually used by Watson and Crick. Photo 51, shown in **Figure 6**, indicated that DNA was a **double helix**, or twisted ladder shape, formed by two strands of nucleotides twisted around each other. The specific structure of the DNA double helix was determined later by Watson and Crick when they used Franklin's data and other mathematical data. DNA is the genetic material of all organisms, composed of two complementary, precisely paired strands of nucleotides wound in a double helix.

Watson and Crick Watson and Crick were working at Cambridge University in Cambridge, England, when they saw Franklin's X-ray diffraction picture. Using Chargaff's data and Franklin's data, Watson and Crick measured the width of the helix and the spacing of the bases. Together, they built a model of the double helix that conformed to the others' research. The model that they built is shown in **Figure 7.** Some important features of their proposed molecule include the following:

1. Two outside strands consist of alternating deoxyribose and phosphate.
2. Cytosine and guanine bases pair to each other by three hydrogen bonds.
3. Thymine and adenine bases pair to each other by two hydrogen bonds.

DNA structure DNA often is compared to a twisted ladder, with the rails of the ladder represented by the alternating deoxyribose and phosphate. The pairs of bases (cytosine-guanine or thymine-adenine) form the steps, or rungs, of the ladder. A purine base always binds to a pyrimidine base, ensuring a consistent distance between the two rails of the ladder. This proposed bonding of the bases also explains Chargaff's data, which suggested that the number of purine bases equaled the number of pyrimidine bases in a sample of DNA. Remember, cytosine and thymine are pyrimidine bases, adenine and guanine are purines, and C = G and A = T. Therefore, C + T = G + A, or purine bases equal pyrimidine bases. Complementary base pairing is used to describe the precise pairing of purine and pyrimidine bases between strands of nucleic acids. It is the characteristic of DNA replication through which the parent strand can determine the sequence of a new strand.

Launch Lab

Review **Based on what you've read about the history of DNA experiments, how would you now answer the analysis questions?**

Reading Check **Explain** why Chargaff's data was an important clue for putting together the structure of DNA.

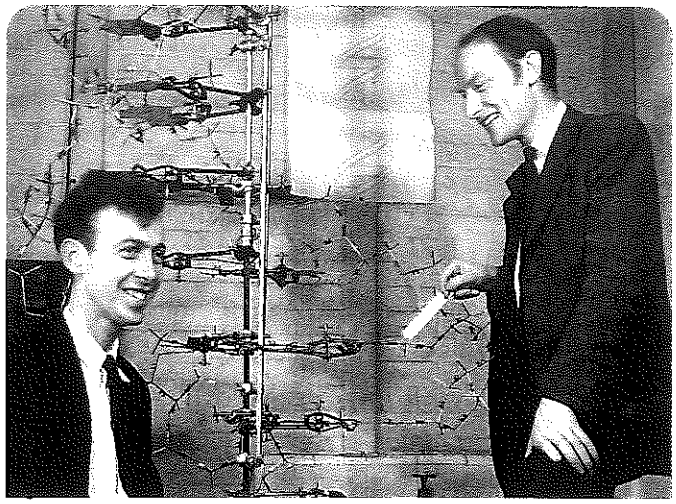


Figure 7 Using Chargaff's and Franklin's data, Watson and Crick, shown here, solved the puzzle of the structure of DNA.

(t)Omikron/Photo Researchers; (b)A. Barrington Brown/Photo Researchers

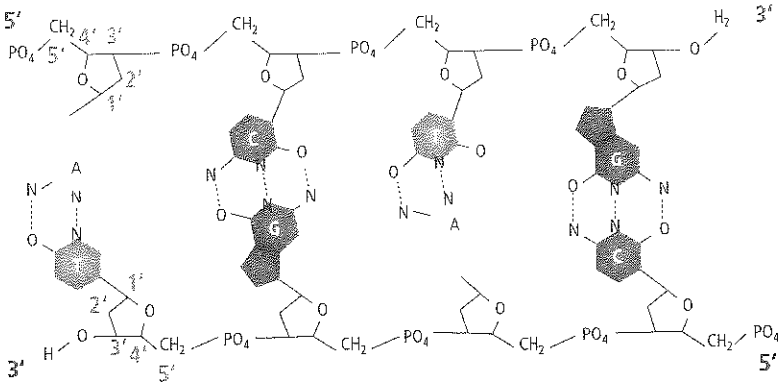


Figure 8 Two strands of DNA running antiparallel make up the DNA helix. *Explain why the ends of the DNA strands are labeled 3' and 5'.*

Animation

Orientation Another unique feature of the DNA molecule is the direction, or orientation, of the two strands. Carbon molecules can be numbered in organic molecules. **Figure 8** shows the orientation of the numbered carbons in the sugar molecules on each strand of DNA. On the top rail, the orientation of the sugar has the 5' (read "five-prime") carbon on the left, and on the end of that rail, the 3' (read "three-prime") carbon is on the right of the sugar-phosphate chain. The strand is said to be oriented 5' to 3'. The strand on the bottom runs in the opposite direction and is oriented 3' to 5'. This orientation of the two strands is called antiparallel. Another way to visualize antiparallel orientation is to take two pencils and position them so that the point of one pencil is next to the eraser of the other and vice versa.

The announcement In 1953, Watson and Crick surprised the scientific community by publishing a one-page letter in the journal *Nature* that suggested a structure for DNA and hypothesized a method of replication for the molecule deduced from the structure. In articles individually published in the same issue, Wilkins and Franklin presented evidence that supported the structure proposed by Watson and Crick. Still, the mysteries of how to prove DNA's replication and how it worked as a genetic code remained.

VOCABULARY

SCIENCE USAGE V. COMMON USAGE

Prime

Science usage: a mark located above and to the right of a character, used to identify a number or variable
Carbon molecules in organic molecules are numbered and labeled with a prime.

Common usage: first in value, excellence, or quality
The student found the prime seats in the stadium for watching the game.

MiniLab 1

MiniLab

Model DNA Structure

What is the structure of the DNA molecule? Construct a model to better understand the structure of the DNA molecule.

Procedure

1. Read and complete the lab safety form.
2. Construct a model of a short segment of DNA using the materials provided by your teacher.
3. Identify which parts of the model correspond to the different parts of a DNA molecule.

Analysis

1. **Describe** the structure of your DNA molecule.
2. **Identify** the characteristics of DNA that you focused on when constructing your model.
3. **Infer** in what way your model is different from your classmates' models. How does this relate to differences in DNA among organisms?

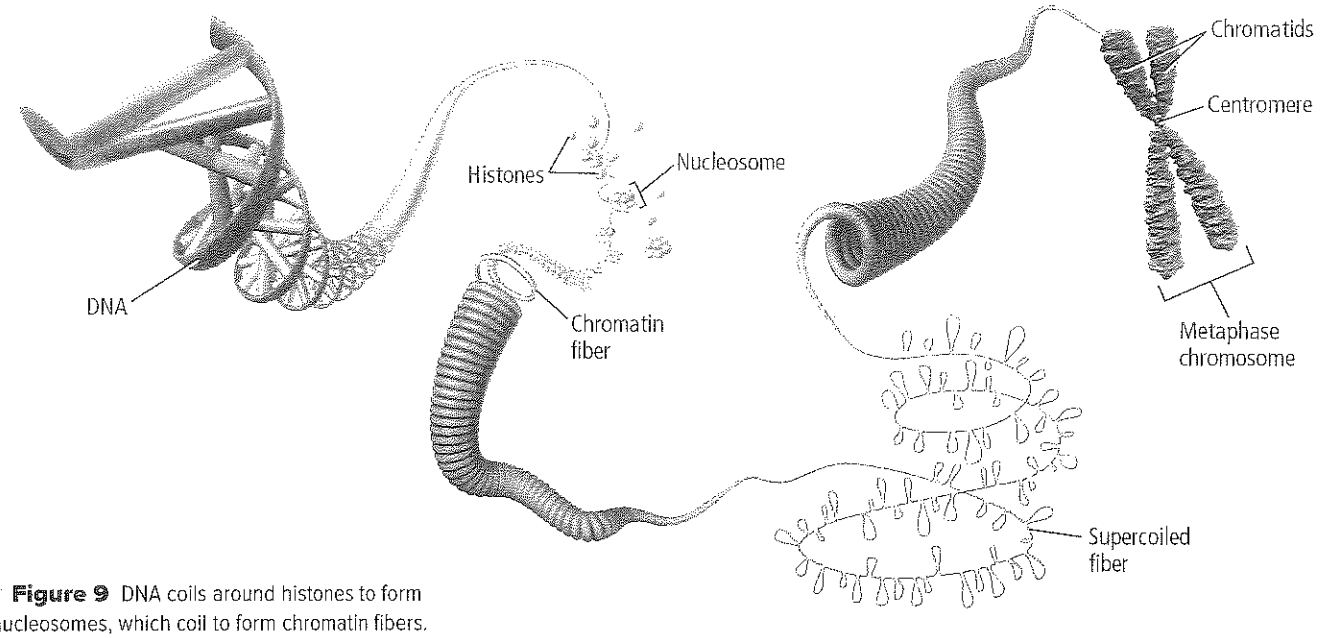


Figure 9 DNA coils around histones to form nucleosomes, which coil to form chromatin fibers. The chromatin fibers supercoil to form chromosomes that are visible in the metaphase stage of mitosis.

Chromosome Structure

In prokaryotes, the DNA molecule is contained in the cytoplasm and consists mainly of a ring of DNA and associated proteins. Eukaryotic DNA is organized into individual chromosomes. The length of a human chromosome ranges from 51 million to 245 million base pairs. If a DNA strand 140 million nucleotides long was laid out in a straight line, it would be about five centimeters long. How does all of this DNA fit into a microscopic cell? In order to fit into the nucleus of a eukaryotic cell, the DNA tightly coils around a group of beadlike proteins called histones, as shown in **Figure 9.** The phosphate groups in DNA create a negative charge, which attracts the DNA to the positively charged histone proteins and forms a **nucleosome.** The nucleosomes then group together into chromatin fibers, which supercoil to make up the DNA structure recognized as a chromosome.

Section 1 Assessment

Section Summary

- Griffith's bacterial experiment and Avery's explanation first indicated that DNA is the genetic material.
- The Hershey-Chase experiment provided evidence that DNA is the genetic material of viruses.
- Chargaff's rule states that in DNA the amount of cytosine equals the amount of guanine and the amount of thymine equals the amount of adenine.
- The work of Watson, Crick, Franklin, and Wilkins provided evidence of the double-helix structure of DNA.

Understand Main Ideas

1. MAIN Idea **Summarize** the experiments of Griffith and Avery that indicated that DNA is the genetic material.
2. **Describe** the data used by Watson and Crick to determine the structure of DNA.
3. **Draw** and label a segment of DNA showing its helix and complementary base pairing.
4. **Describe** the structure of eukaryotic chromosomes.

Think Critically

5. **Describe** two characteristics that DNA needs to fulfill its role as a genetic material.
6. **Evaluate** Hershey and Chase's decision to use radioactive phosphorus and sulfur for their experiments. Could they have used carbon or oxygen instead? Why or why not?

Online Quiz

Reading Preview

Essential Questions

- What is the role of enzymes in the replication of DNA?
- How are leading and lagging strands synthesized differently?
- How does DNA replication compare in eukaryotes and prokaryotes?

Review Vocabulary

template: a molecule of DNA that is a pattern for synthesis of a new DNA molecule

New Vocabulary

semiconservative replication
DNA polymerase
Okazaki fragment

Multilingual eGlossary

Replication of DNA

MAIN Idea **DNA replicates by making a strand that is complementary to each original strand.**

Real-World Reading Link When copies are made using a photocopy machine, they are expected to be exact copies of the original. Making a copy would not be very efficient if it contained errors that were not in the original. Think about how your body might make copies of DNA.

Semiconservative Replication

When Watson and Crick presented their model of DNA to the science community, they also suggested a possible method of replication called semiconservative replication. During **semiconservative replication,** parental strands of DNA separate, serve as templates, and produce DNA molecules that have one strand of parental DNA and one strand of new DNA. Recall that DNA replication occurs during interphase of mitosis and meiosis. An overview of semiconservative replication is in **Figure 10.** The process of semiconservative replication occurs in three main stages: unwinding, base pairing, and joining.

Unwinding DNA helicase, an enzyme, is responsible for unwinding and unzipping the double helix. When the double helix is unzipped, the hydrogen bonds between the bases are broken, leaving single strands of DNA. Then, proteins called single-stranded binding proteins associate with the DNA to keep the strands separate during replication. As the helix unwinds, another enzyme, RNA primase, adds a short segment of RNA, called an RNA primer, on each DNA strand.

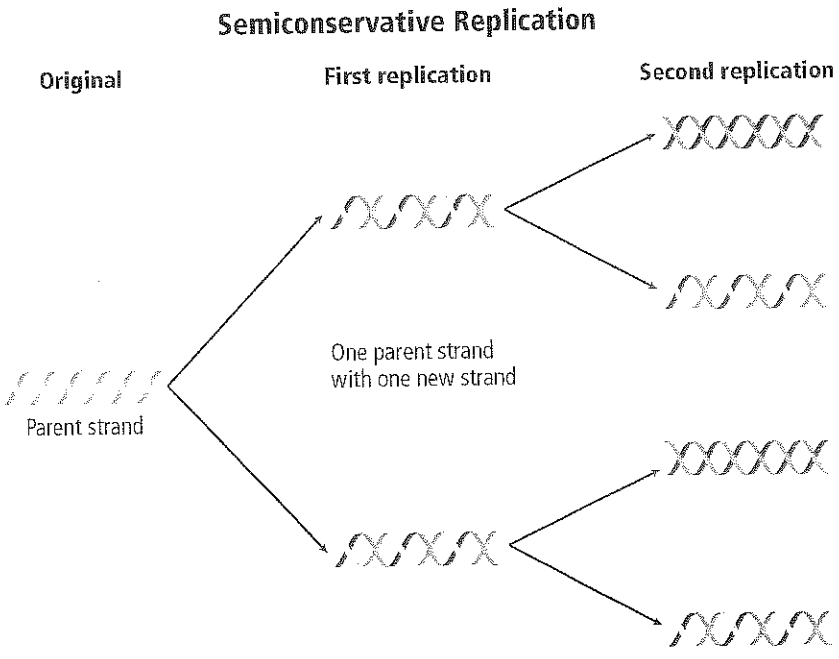


Figure 10 In semiconservative replication, the parental DNA separates and serves as templates to produce two daughter DNA, which then can separate to produce four DNA.

MiniLab 2

MiniLab

Model DNA Replication

How does the DNA molecule replicate? Use a model to better understand the replication of the DNA molecule.

Procedure

1. Read and complete the lab safety form.
2. Use your DNA model from **MiniLab 1** and extra pieces to model the replication of your segment of DNA.
3. Use your model to demonstrate DNA replication for a classmate, and identify the enzymes involved in each step.

Analysis

1. **Explain** how your model of DNA replication shows semiconservative replication.
2. **Infer** how DNA replication in a cell would be affected by an absence of DNA ligase.
3. **Identify** where errors could occur in the replication process.

Base pairing The enzyme **DNA polymerase** catalyzes the addition of appropriate nucleotides to the new DNA strand. The nucleotides are added to the 3' end of the new strand, as illustrated in **Figure 11.** DNA polymerase continues adding new DNA nucleotides to the chain by adding to the 3' end of the new DNA strand. Recall that each base binds only to its complement–A binds to T and C binds to G. In this way, the templates allow identical copies of the original double-stranded DNA to be produced.

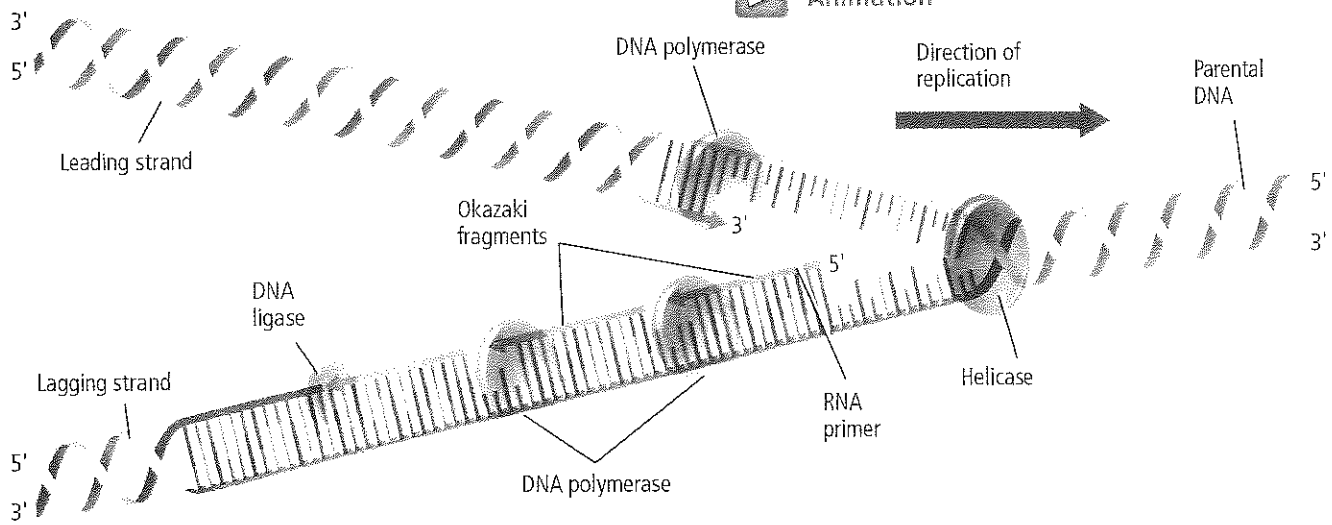
Notice in **Figure 11** that the two strands are made in a slightly different manner. One strand is called the leading strand and is elongated as the DNA unwinds. This strand is built continuously by the addition of nucleotides to the 3' end.

The other strand of DNA, called the lagging strand, elongates away from the replication fork. It is synthesized discontinuously into small segments, called **Okazaki fragments,** by the DNA polymerase in the 3' to 5' direction. These fragments are later connected by the enzyme DNA ligase. Each Okazaki fragment is about 100–200 nucleotides long in eukaryotes. Because one strand is synthesized continuously and the other is synthesized discontinuously, DNA replication is said to be semidiscontinuous as well as semiconservative.

Reading Check **Explain** how base pairing during replication ensures that the strands produced are identical to the original strand.

Figure 11 The DNA strands are separated during replication as each parent strand serves as a template for new strands.
Infer ***why the lagging strand produces fragments instead of being synthesized continuously.***

Animation



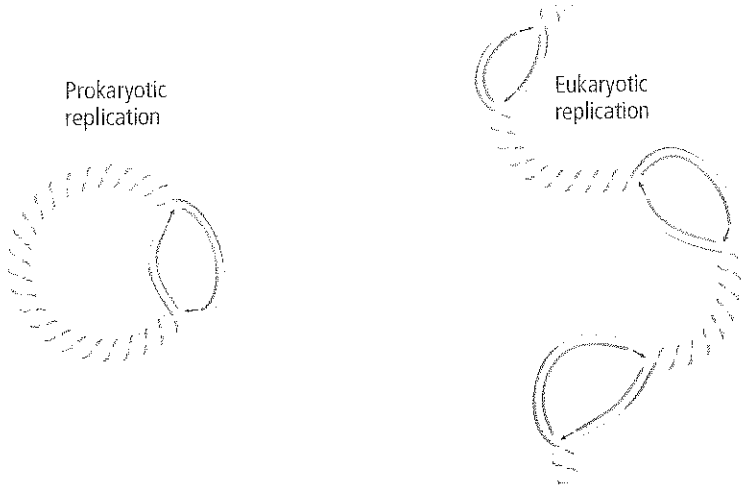


Figure 12 Eukaryotes have many origins of replication. Bacteria have one origin of replication, with the DNA replicating in both directions when it unzips.

Joining Even though the leading strand is synthesized continuously, in eukaryotic DNA replication there often are many areas along the chromosome where replication begins. When the DNA polymerase comes to an RNA primer on the DNA, it removes the primer and fills in the place with DNA nucleotides. When the RNA primer has been replaced, DNA ligase links the two sections.

Comparing DNA Replication in Eukaryotes and Prokaryotes

Eukaryotic DNA unwinds in multiple areas as DNA is replicated. Each individual area of a chromosome replicates as a section, which can vary in length from 10,000 to one million base pairs. As a result, multiple areas of replication are occurring along the large eukaryotic chromosome at the same time. Multiple replication origins look like bubbles in the DNA strand, as shown in **Figure 12.**

In prokaryotes, the circular DNA strand is opened at one origin of replication, as shown in **Figure 12.** Notice in the figure that DNA replication occurs in two directions, just as it does in eukaryotes. Remember that prokaryotic DNA is typically shorter than eukaryotic DNA and remains in the cytoplasm, not packaged in a nucleus.

Section 2 Assessment

Section Summary

- The enzymes DNA helicase, RNA primase, DNA polymerase, and DNA ligase are involved in DNA replication.
- The leading strand is synthesized continuously, but the lagging strand is synthesized discontinuously, forming Okazaki fragments.
- Prokaryotic DNA opens at a single origin of replication, whereas eukaryotic DNA has multiple areas of replication.

Understand Main Ideas

1. **Indicate** the sequence of the template strand if a nontemplate strand has the sequence 5' ATGGGGCGC 3'.
2. **Describe** the role of DNA helicase, DNA polymerase, and DNA ligase.
3. **Diagram** the way leading and lagging strands are synthesized.
4. **Explain** why DNA replication is more complex in eukaryotes than in bacteria.

Think Critically

MATH in Biology

5. If the bacteria E. coli synthesize DNA at a rate of 100,000 nucleotides per min and it takes 30 min to replicate the DNA, how many base pairs are in an E. coli chromosome?

Online Quiz

Section 3

Reading Preview

Essential Questions

- How are messenger RNA, ribosomal RNA, and transfer RNA involved in the transcription and translation of genes?
- What is the role of RNA polymerase in the synthesis of messenger RNA?
- How is the code of DNA translated into messenger RNA and utilized to synthesize a protein?

Review Vocabulary

synthesis: the composition or combination of parts to form a whole

New Vocabulary

RNA
messenger RNA
ribosomal RNA
transfer RNA
transcription
RNA polymerase
intron
exon
codon
translation

Multilingual eGlossary

DNA, RNA, and Protein

DNA codes for RNA, which guides protein synthesis.

Real-World Reading Link Computer programmers write their programs in a particular language, or code. The computer is designed to read the code and perform a function. Like the programming code, DNA contains a code that signals the cell to perform a function.

Central Dogma

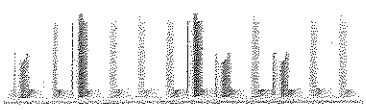
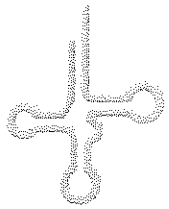
One of the important features of DNA that remained unresolved beyond the work of Watson and Crick was how DNA served as a genetic code for the synthesis of proteins. Recall that proteins function as structural building blocks for the cells and as enzymes.

Geneticists now accept that the basic mechanism of reading and expressing genes is from DNA to RNA to protein. This chain of events occurs in all living things–from bacteria to humans. Scientists refer to this mechanism as the central dogma of biology: DNA codes for RNA, which guides the synthesis of proteins.

RNA RNA is a nucleic acid that is similar to DNA. However, **RNA** contains the sugar ribose, the base uracil replaces thymine, and usually is single stranded. Three major types of RNA are found in living cells. **Messenger RNA** (mRNA) molecules are long strands of RNA nucleotides that are formed complementary to one strand of DNA. They travel from the nucleus to the ribosome to direct the synthesis of a specific protein. **Ribosomal RNA** (rRNA) is the type of RNA that associates with proteins to form ribosomes in the cytoplasm. The third type of RNA, **transfer RNA** (tRNA) are smaller segments of RNA nucleotides that transport amino acids to the ribosome. **Table 2** compares the structures and functions of the three types of RNA.

Table 2 Comparison of Three Types of RNA

Interactive Table

Name	mRNA	rRNA	tRNA
Function	Carries genetic information from DNA in the nucleus to direct protein synthesis in the cytoplasm	Associates with protein to form the ribosome	Transports amino acids to the ribosome
Example			

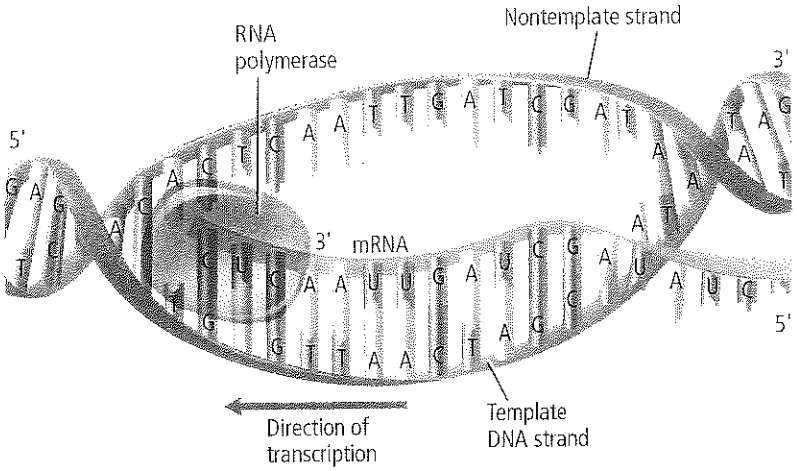


Figure 13 RNA is grown in the 5' to 3' direction.
Identify which enzyme adds nucleotides to the growing RNA.

Transcription The first step of the central dogma involves the synthesis of mRNA from DNA in a process called **transcription** (trans KRIHP shun). Through transcription, the DNA code is transferred to mRNA in the nucleus. The mRNA then can take the code into the cytoplasm for protein synthesis. Follow along with the process of transcription in **Figure 13.** The DNA is unzipped in the nucleus and **RNA polymerase,** an enzyme that regulates RNA synthesis, binds to a specific section where an mRNA will be synthesized. As the DNA strand unwinds, the RNA polymerase initiates mRNA synthesis and moves along one of the DNA strands in the 3' to 5' direction. The strand of DNA that is read by RNA polymerase is called the template strand, and mRNA is synthesized as a complement to the DNA nucleotides. The DNA strand not used as the template strand is called the nontemplate strand. The mRNA transcript is manufactured in a 5' to 3' direction, adding each new RNA nucleotide to the 3' end. Uracil is incorporated instead of thymine as the mRNA molecule is made. Eventually, the mRNA is released, and the RNA polymerase detaches from the DNA. The new mRNA then moves out of the nucleus through nuclear pores into the cytoplasm.

FOLDABLES
Incorporate information from this section into your Foldable.

Reading check **Explain** the direction in which the mRNA transcript is manufactured.

RNA processing When scientists compared the coding region of the DNA with mRNA that ultimately coded for a protein, they found that the mRNA code is significantly shorter than the DNA code. Upon closer examination, they discovered that the code on the DNA is interrupted periodically by sequences that are not in the final mRNA. These sequences are called intervening sequences, or **introns.** The coding sequences that remain in the final mRNA are called **exons.** In eukaryotes, the original mRNA made in the nucleus is sometimes called pre-mRNA and contains all of the DNA code. Before the pre-mRNA leaves the nucleus, the introns are removed from it. Other processing of the pre-mRNA includes adding a protective cap on the 5' end and adding a tail of many adenine nucleotides, called the poly-A tail, to the 3' end of the mRNA. Research shows that the cap aids in ribosome recognition, though the significance of the poly-A tail remains unknown. The mRNA that reaches the ribosome has been processed.

Virtual Lab

First Base	Second Base				Third Base
	U	C	A	G	
U	UUU phenylalanine	UCU serine	UAU tyrosine	UGU cysteine	U
	UUC phenylalanine	UCC serine	UAC tyrosine	UGC cysteine	C
	UUA leucine	UCA serine	UAA *stop*	UGA *stop*	A
	UUG leucine	UCG serine	UAG *stop*	UGG tryptophan	G
C	CUU leucine	CCU proline	CAU histidine	CGU arginine	U
	CUC leucine	CCC proline	CAC histidine	CGC arginine	C
	CUA leucine	CCA proline	CAA glutamine	CGA arginine	A
	CUG leucine	CCG proline	CAG glutamine	CGG arginine	G
A	AUU isoleucine	ACU threonine	AAU asparagine	AGU serine	U
	AUC isoleucine	ACC threonine	AAC asparagine	AGC serine	C
	AUA isoleucine	ACA threonine	AAA lysine	AGA arginine	A
	AUG *(start)* methionine	ACG threonine	AAG lysine	AGG arginine	G
G	GUU valine	GCU alanine	GAU aspartate	GGU glycine	U
	GUC valine	GCC alanine	GAC aspartate	GGC glycine	C
	GUA valine	GCA alanine	GAA glutamate	GGA glycine	A
	GUG valine	GCG alanine	GAG glutamate	GGG glycine	G

Figure 14 This "dictionary" of the genetic code is helpful for knowing which codons code for which amino acids.
Determine *the possible sequences that would produce the amino acid chain: start—serine—histidine—tryptophan—stop.*

APPLYING PRACTICES

Construct an Explanation Based on Evidence Go to the resources tab in ConnectED to find the Applying Practices worksheet *Transcription and Translation.*

The Code

Biologists began to hypothesize that the instructions for protein synthesis are encoded in the DNA. They recognized that the only way the DNA varied among organisms was in the sequence of the bases. Scientists knew that 20 amino acids were used to make proteins, so they knew that the DNA must provide at least 20 different codes.

Connection to Math The hypothesis for how the bases formed the code is based on math and logic. If each base coded for one amino acid, then the four bases could code for four amino acids. If each pair of bases coded for one amino acid, then the four bases could only code for 16 (4×4 or 4^2) amino acids. However, if a group of three bases coded for one amino acid, there would be 64 (4^3) possible codes. This provides more than the 20 codes needed for the 20 amino acids, but is the smallest possible combination of bases to provide enough codes for the amino acids.

This reasoning meant that the code was not contained in the base pairs themselves, but must run along a single strand of the DNA. Experiments during the 1960s demonstrated that the DNA code was indeed a three-base code. The three-base code in DNA or mRNA is called a **codon.** Each of the three bases of a codon in the DNA is transcribed into the mRNA code. **Figure 14** shows a "dictionary" of the genetic code. Notice that all but three codons are specific for an amino acid; these three are stop codons. Codon AUG codes for the amino acid methionine and also functions as the start codon.

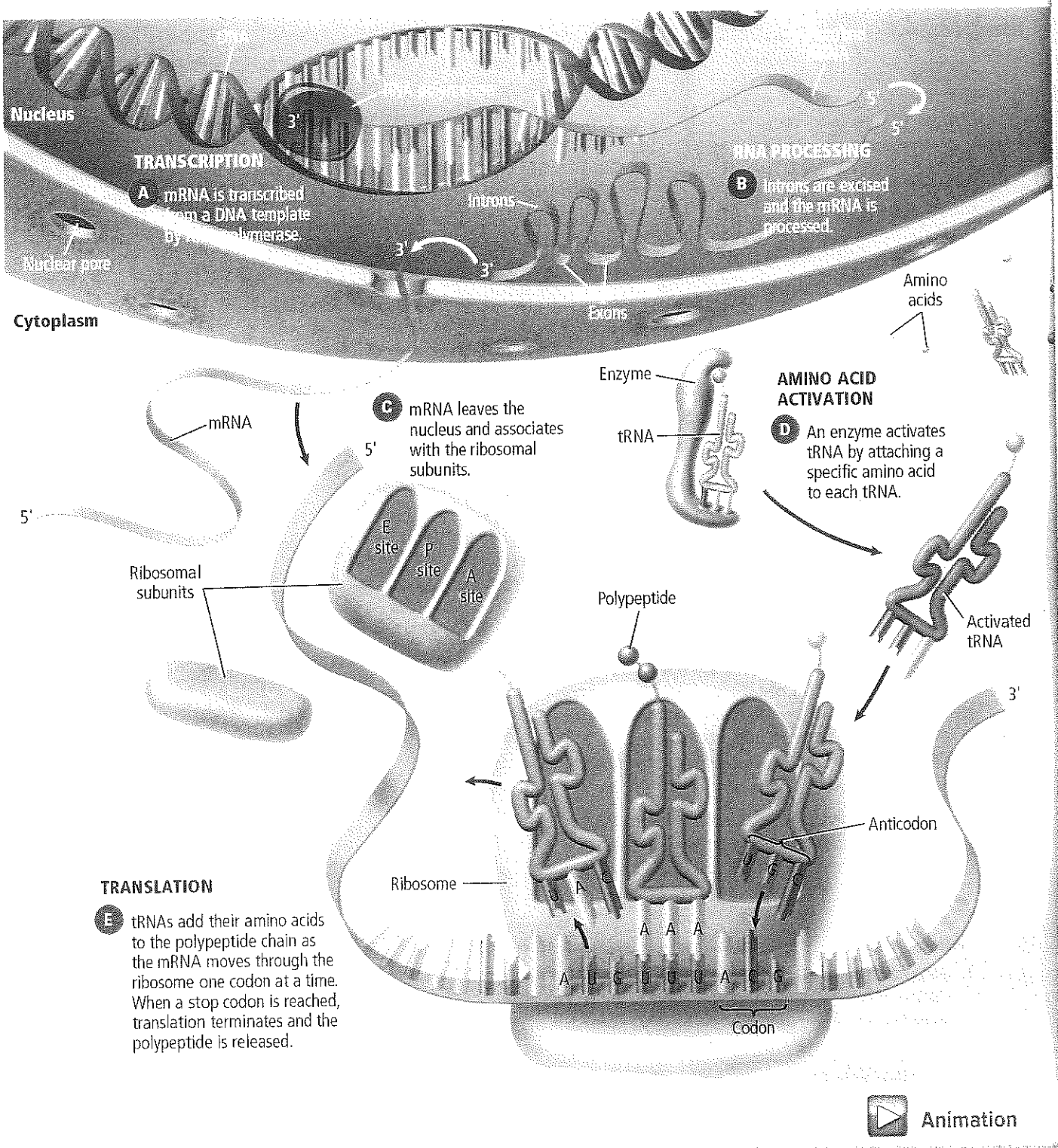
Translation Once the mRNA is synthesized and processed, it moves to the ribosome. In eukaryotes, this means the mRNA must leave the nucleus and enter the cytoplasm. Once in the cytoplasm, the 5' end of the mRNA connects to the ribosome. This is where the code is read and translated to make a protein through a process called **translation.** Follow along in **Figure 15** as you learn about translation.

In translation, tRNA molecules act as the interpreters of the mRNA codon sequence. The tRNA is folded into a cloverleaf shape and is activated by an enzyme that attaches a specific amino acid to the 3' end. At the middle of the folded strand, there is a three-base coding sequence called the anticodon. Each anticodon is complementary to a codon on the mRNA. Though the code in DNA and RNA is read 5' to 3', the anticodon is read 3' to 5'.

Visualizing Transcription and Translation

Figure 15

Transcription takes place in the nucleus. Translation occurs in the cytoplasm and results in the formation of polypeptides.



The role of the ribosome The ribosome consists of two subunits, as shown in **Figure 15.** These subunits are not associated when they are not involved in protein translation. When the mRNA leaves the nucleus, the two parts of the ribosome come together and attach to the mRNA to complete the ribosome. Once the mRNA is associated with the ribosome, a tRNA with the anticodon CAU carrying a methionine will move in and bind to the mRNA start codon–AUG–on the 5' end of the mRNA. The ribosome structure has a groove, called the P site, where the tRNA that is complementary to the mRNA moves in.

A second tRNA moves into a second groove in the ribosome, called the A site, and corresponds to the next codon of the mRNA. The next codon is UUU, so a tRNA with the anticodon AAA moves in, carrying the amino acid phenylalanine.

Part of the rRNA in the ribosome now acts as an enzyme catalyzing the formation of a bond between the new amino acid in the A site and the amino acid in the P site. As the two amino acids join, the tRNA in the P site is released to the third site, called the E site, where it exits the ribosome. The ribosome then moves so the tRNA found in Groove A is shifted to Site P, as shown in **Figure 15.** Now a new tRNA will enter the A site, complementing the next codon on the mRNA. This process will continue adding and linking amino acids in the sequence determined by the mRNA.

The ribosome continues to move along until the A site contains a stop codon. The stop codon signals the end of protein synthesis and does not complement any tRNA. Proteins called release factors cause the mRNA to be released from the last tRNA and the ribosome subunits to disassemble, ending protein synthesis.

Study Tip

Flowchart Draw a flowchart that connects the processes of DNA replication, transcription, and translation.

DATA ANALYSIS LAB 1

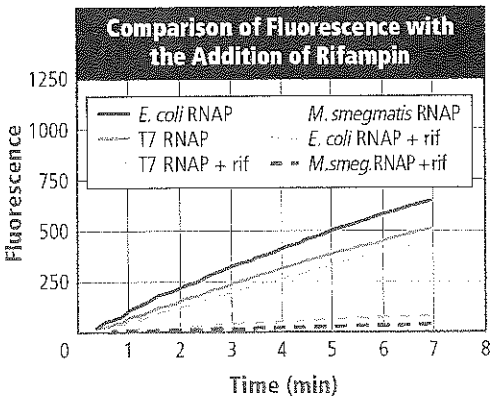
Based on Real Data*

Interpret the Data

How can a virus affect transcription? To study RNA synthesis, a group of scientists used a fluorescent molecular beacon to trace molecules. This beacon becomes fluorescent when it binds to newly synthesized RNA. The fluorescence increases as the RNA chain lengthens. Thus, the beacon can be used to follow RNA synthesis.

In this experiment, scientists added the antibiotic rifampin (rif) to RNA polymerase from a virus (T7 RNAP), *Escherchia coli (E. coli* RNAP), and *Mycobacterium smegmatis (M. smegmatis* RNAP) and followed RNA synthesis.

Data and Observations



Think Critically

1. **Describe** the relationship between the fluorescence level and time in each experiment not exposed to rifampin.
2. **Infer** what the relationship between fluorescence level and time indicates is happening in each case where rifampin was added.
3. **Interpret** which organism's RNA synthesis is affected most by the antibiotic rifampin.

*Data obtained from: Marras, Salvatore A.E., et al. 2004. Real-time measurement of *in vitro* transcription. *Nucleic Acids Research* 32.9.e: 72.

One Gene—One Enzyme

Once scientists learned how DNA works as a code, they needed to learn the relationships between the genes and the proteins for which they coded. Experiments on the mold *Neurospora* were the first to demonstrate the relationship between genes and enzymes. In the 1940s, George Beadle and Edward Tatum provided evidence that a gene can code for an enzyme. They studied mold spores that were mutated by exposure to X-rays. Examine **Figure 16** to follow along with their experiment.

Normally, *Neurospora* can grow on an artificial medium that provides no amino acids. This type of medium is called minimal medium. Complete medium provides all the amino acids that *Neurospora* needs to function. In Beadle and Tatum's experiment, the spores were exposed to X-rays and grown on a complete medium. To test for a mutated spore, the scientists grew spores on a minimal medium. When a spore was unable to grow on the minimal medium, the mutant was tested to see what amino acid it lacked. When the mold-spore type grew on a minimal medium with a supplement such as arginine, Beadle and Tatum hypothesized that the mutant was missing the enzyme needed to synthesize arginine.

Beadle and Tatum came up with what is known as the "one gene–one enzyme" hypothesis. Today, because we know that polypeptides make up enzymes, their hypothesis has been modified slightly to refer to the fact that one gene codes for one polypeptide.

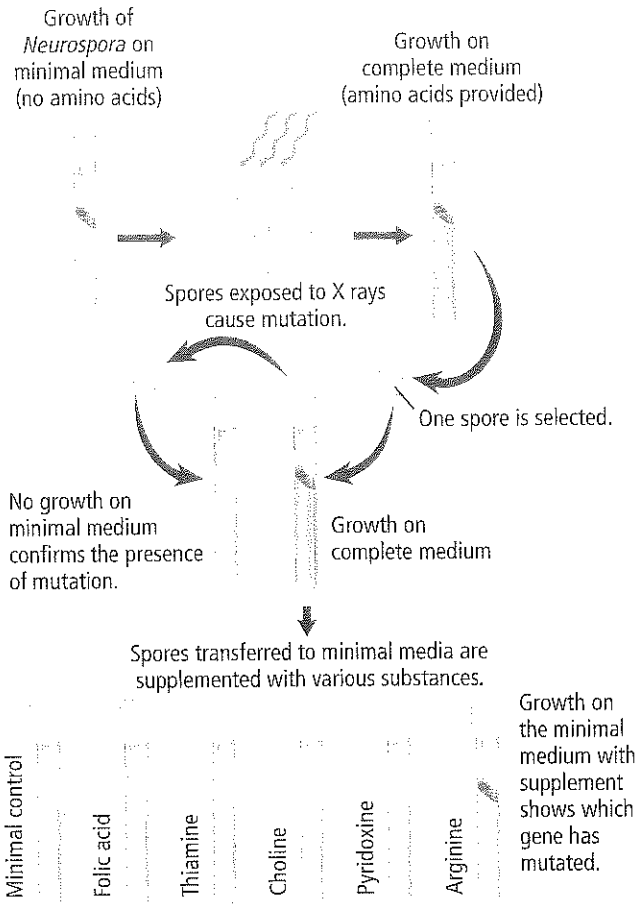


Figure 16 The Beadle and Tatum experiment showed that a gene codes for an enzyme. We now know that a gene codes for a polypeptide.

Section 3 Assessment

Section Summary

- Three major types of RNA are involved in protein synthesis: mRNA, tRNA, and rRNA.
- The synthesis of the mRNA from the template DNA is called transcription.
- Translation is the process through which the mRNA attaches to the ribosome and a protein is assembled.
- In eukaryotes, mRNA contains introns that are excised before leaving the nucleus. A cap and poly-A tail are added to the mRNA.
- One gene codes for one polypeptide.

Understand Main Ideas

1. **Summarize** the process by which the DNA code is made into a protein.
2. **Describe** the function of each of the following in protein synthesis: rRNA, mRNA, and tRNA.
3. **Differentiate** between codons and anticodons.
4. **Explain** the role of RNA polymerase in mRNA sythesis.
5. **Conclude** why Beadle and Tatum's "one gene, one enzyme" hypothesis has been modified since they presented it in the 1940s.

Think Critically

MATH in Biology

6. If the genetic code used four bases as a code instead of three, how many code units could be encoded?

Online Quiz

Reading Preview

Essential Questions

- How are bacteria able to regulate their genes by two types of operons?
- How do eukaryotes regulate the transcription of genes?
- What are the various types of mutations?

Review Vocabulary

prokaryote: organism that does not have membrane-bound organelles and DNA that is organized in chromosomes

New Vocabulary

gene regulation
operon
mutation
mutagen

Multilingual eGlossary

Gene Regulation and Mutation

MAIN Idea **Gene expression is regulated by the cell, and mutations can affect this expression.**

Real-World Reading Link When you type a sentence on a keyboard, it is important that each letter is typed correctly. The sentence "The fat cat ate the rat" is quite different from "The fat cat ate the hat." Though there is a difference of only one letter between the two sentences, the meaning is changed.

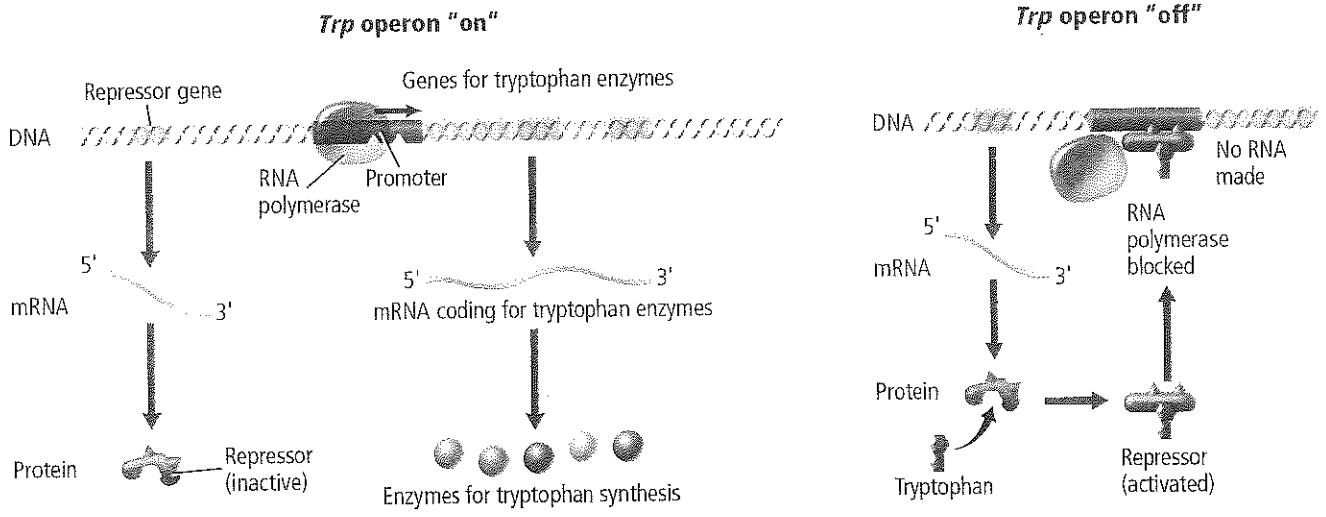
Prokaryote Gene Regulation

How do prokaryotic cells regulate which genes will be transcribed at particular times in the lifetime of an organism? **Gene regulation** is the ability of an organism to control which genes are transcribed in response to the environment. In prokaryotes, an operon often controls the transcription of genes in response to changes in the environment. An **operon** is a section of DNA that contains the genes for the proteins needed for a specific metabolic pathway. The parts of an operon include an operator, promoter, regulatory gene, and the genes coding for proteins. The operator is a segment of DNA that acts as an on/off switch for transcription. A second segment of DNA, called the promoter, is where the RNA polymerase first binds to the DNA. The bacteria *Escherichia coli (E. coli)* respond to tryptophan, which is an amino acid, and lactose, which is a sugar, through two operons.

The *trp* operon In bacteria, tryptophan synthesis occurs in a series of five steps, and each step is catalyzed by a specific enzyme. The five genes coding for these enzymes are clustered together on the bacterial chromosome with a group of DNA that controls whether or not they are transcribed. This cluster of DNA is called the tryptophan *(trp)* operon and is illustrated in **Figure 17.**

Figure 17 The *trp* operon is an example of the gene expression of repressible enzymes.

Animation



The *trp* operon is referred to as a repressible operon because transcription of the five enzyme genes normally is repressed, or turned off. When tryptophan is present in the cell's environment, the cell has no need to synthesize it and the *trp* repressor gene turns off, or represses, the transcription process by making a repressor protein. Tryptophan in *E. coli* combines with an inactive repressor protein to activate it, and the complex binds to the operator in the promoter sequence. If the repressor is bound to the operator, RNA polymerase cannot bind to it, which prevents the transcription of the enzyme genes. This prohibits the synthesis of tryptophan by the cell.

When tryptophan levels are low, the repressor is not bound to tryptophan and is inactive–it does not bind to the operator. The RNA polymerase is able to bind to the operator, turning on transcription of the five enzyme genes. This transcription enables the synthesis of tryptophan by the cell. Notice the location of the repressor protein in **Figure 17** when the operon is turned both off and on.

Reading Check **Summarize** the effect of tryptophan on the *trp* operon.

The *lac* operon When lactose is present in the cell, *E. coli* makes enzymes that enable it to use lactose as an energy source. The lactose (*lac*) operon, illustrated in **Figure 18,** contains a promoter, an operator, a regulatory gene, and three enzyme genes that control lactose digestion. In the *lac* operon, the regulatory gene makes a repressor protein that binds to the operator in the promoter sequence and prevents the transcription of the enzyme genes.

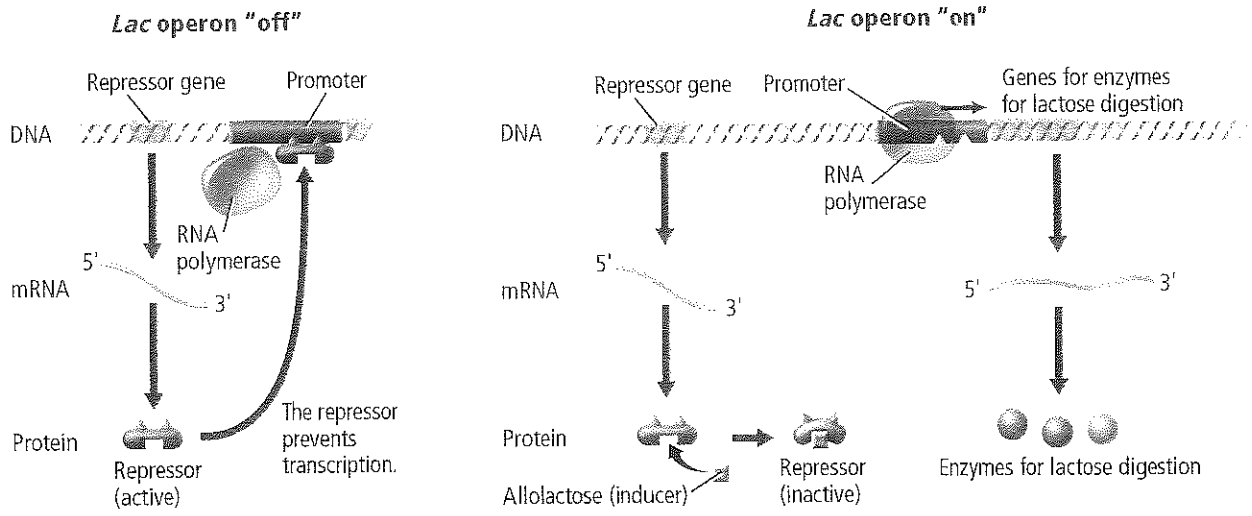
When a molecule called an inducer is present, the inducer binds to the repressor and inactivates it. In the *lac* operon, the inducer is allolactose, a molecule that is present in food that contains lactose. Thus, when lactose is present, the allolactose binds to the repressor and inactivates it. With the repressor inactivated, RNA polymerase then can bind to the promoter and begin transcription. The *lac* operon is called an inducible operon because transcription is turned on by an inducer.

CAREERS IN BIOLOGY

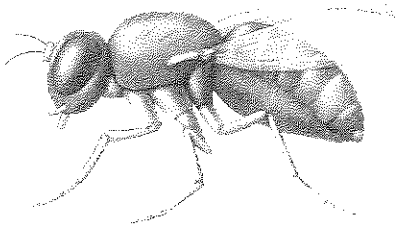
Microbiologist Scientists who study microbes, primarily prokaryotes, are called microbiologists. They might research to learn about which genes control the production of particular proteins or how a protein affects the life of a cell.

Figure 18 The *lac* operon is an example of the gene expression of inducible enzymes. **Identify** *what the repressor is bound to when the* **lac** *operon is turned off.*

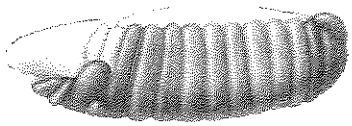
Animation



Adult *Drosophila*



Drosophila embryo



Drosophila Hox genes

Figure 19 Hox genes are responsible for the general body pattern of most animals. Notice that the order of the genes is the same as the order of the body sections the genes control.

Eukaryote Gene Regulation

Eukaryotic cells also must control what genes are expressed at different times in the organism's lifetime. In eukaryotic cells, many genes interact with one another, requiring more elements than a single promoter and operator for a set of genes. The organization and structure of eukaryotic cells is more complex than in prokaryotic cells, increasing the complexity of the control system.

Controlling transcription One way that eukaryotes control gene expression is through proteins called transcription factors. Transcription factors ensure that a gene is used at the right time and that proteins are made in the right amounts. There are two main sets of transcription factors. One set of transcription factors forms complexes that guide and stabilize the binding of the RNA polymerase to a promoter. The other set includes regulatory proteins that help control the rate of transcription. For instance, proteins called activators fold DNA so that enhancer sites are close to the complex and increase the rate of gene transcription. Repressor proteins also bind to specific sites on the DNA and prevent the binding of activators.

The complex structure of eukaryotic DNA also regulates transcription. Recall that eukaryotic DNA is wrapped around histones to form nucleosomes. This structure provides some inhibition of transcription, although regulatory proteins and RNA polymerase still can activate specific genes even when they are packaged in the nucleosome.

Hox genes Gene regulation is crucial during development. Recall that multicellular eukaryotes develop from a single cell called a zygote. The zygote undergoes mitosis, producing all the different kinds of cells needed by the organism. Differentiation is the process through which the cells become specialized in structure and function. One group of genes that controls differentiation has been discovered. These genes are called homeobox (Hox) genes. Hox genes are important for determining the body plan of an organism. They code for transcription factors and are active in zones of the embryo that are in the same order as the genes on the chromosome. For example, the colored regions of the fly and fly embryo in **Figure 19** correspond to the colored genes on the piece of DNA in the figure. These genes, transcribed at specific times, and located in specific places on the genome, control what body part will develop in a given location. One mutation in the Hox genes of fruit flies has yielded flies with legs growing where their antennae should be. Studying these flies has helped scientists understand more about how genes control the body plan of an organism. Similar clusters of Hox genes that control body plans have been found in all animals.

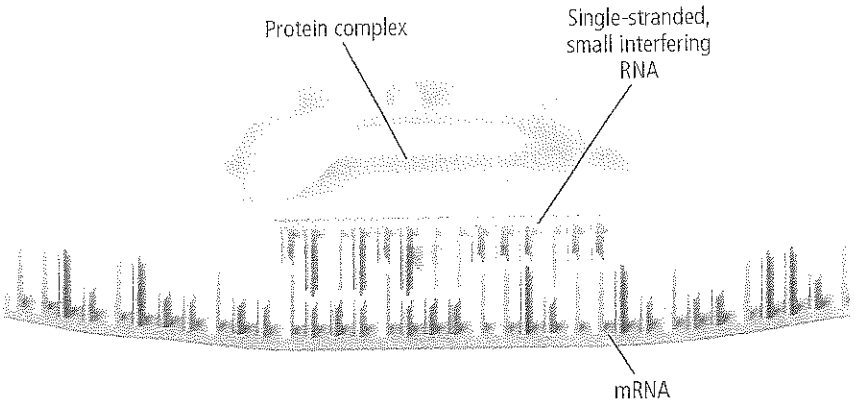


Figure 20 RNA interference can stop the mRNA from translating its message.
Describe *how the RNA-protein complex prevents the translation of the mRNA.*

RNA interference Another method of eukaryotic gene regulation is RNA interference (RNAi). Small pieces of double-stranded RNA in the cytoplasm of the cell are cut by an enzyme called dicer. The resulting double-stranded segments are called small interfering RNA. They bind to a protein complex that degrades one strand of the RNA. The resulting single-stranded small interfering RNA and protein complex bind to sequence-specific sections of mRNA in the cytoplasm, causing the mRNA in this region to be cut and thus preventing its translation. **Figure 20** shows the single-stranded small interfering RNA and protein complex binding to the mRNA. Research and clinical trials are being conducted to investigate the possibility of using RNAi to treat cancer, diabetes, and other diseases.

Reading Check **Explain** how RNA interference can regulate eukaryotic gene expression.

Mutations

Do you ever make mistakes when you are typing an assignment? When you type, sometimes you might strike the wrong key. Just as you might make a mistake when typing, cells sometimes make mistakes during replication. However, these mistakes are rare, and the cell has repair mechanisms that can repair some damage. Sometimes a permanent change occurs in a cell's DNA and this is called a **mutation.** Recall that one inheritance pattern that Mendel studied was round and wrinkled pea seeds. It is now known that the wrinkled phenotype is associated with the absence of an enzyme that influences the shape of starch molecules in the seeds. Because the mutation in the gene causes a change in the protein that is made, the enzyme is nonfunctional.

Types of mutations Mutations can range from changes in a single base pair in the coding sequence of DNA to the deletions of large pieces of chromosomes. Point mutations involve a chemical change in just one base pair and can be enough to cause a genetic disorder. A point mutation in which one base is exchanged for another is called a substitution. Most substitutions are missense mutations, where the DNA code is altered so that it codes for the wrong amino acid. Other substitutions, called nonsense mutations, change the codon for an amino acid to a stop codon. Nonsense mutations cause translation to terminate early. Nearly all nonsense mutations lead to proteins that cannot function normally.

VOCABULARY

ACADEMIC VOCABULARY

Substitution
the act of replacing one thing with another
The substitution of adenine for guanine in the DNA caused a dysfunctional protein.

Personal Tutor

Another type of mutation that can occur involves the gain or loss of a nucleotide in the DNA sequence. Insertions are additions of a nucleotide to the DNA sequence, and the loss of a nucleotide is called a deletion. Both of these mutations change the multiples of three, from the point of the insertion or deletion. These are called frameshift mutations because they change the "frame" of the amino acid sequence. **Table 3** illustrates various types of mutations and their effect on the DNA sequence.

Sometimes mutations are associated with diseases and disorders. One example is alkaptonuria. Patients with this disorder have a mutation in their DNA coding for an enzyme involved in digesting the amino acid phenylalanine. This mutation results in the black-colored homogentisic acid that discolors the urine. Studies have shown that patients with alkaptonuria have a high occurrence of frameshift and missense mutations in a specific region of their DNA. **Table 3** lists some more examples of diseases associated with different types of mutations.

Table 3 **Mutations**

Interactive Table

Mutation Type	Analogy Sentence	Example of Associated Disease
Normal	THE BIG FAT CAT ATE THE WET RAT	
Missense (substitution)	THE BIZ FAT CAT ATE THE WET RAT	Achondroplasia: improper development of cartilage on the ends of the long bones of arms and legs resulting in a form of dwarfism
Nonsense (substitution)	THE BIG RAT	Muscular dystrophy: progressive muscle disorder characterized by the progressive weakening of many muscles in the body
Deletion (causing frameshift)	THB IGF ATC ATA TET HEW ETR AT	Cystic fibrosis: characterized by abnormally thick mucus in the lungs, intestines, and pancreas
Insertion (causing frameshift)	THE BIG ZFA TCA TAT ETH EWE TRA	Crohn's disease: chronic inflammation of the intestinal tract, producing frequent diarrhea, abdominal pain, nausea, fever, and weight loss
Duplication	THE BIG FAT FAT CAT ATE THE WET RAT	Charcot-Marie-Tooth disease (type 1A): damage to peripheral nerves leading to weakness and atrophy of muscles in hands and lower legs
Expanding mutation (tandem repeats)		Huntington's disease: a progressive disease in which brain cells waste away, producing uncontrolled movements, emotional disturbances, and mental deterioration
Generation 1	THE BIG FAT CAT ATE THE WET RAT	
Generation 2	THE BIG FAT CAT CAT CAT ATE THE WET RAT	
Generation 3	THE BIG FAT CAT CAT CAT CAT CAT CAT ATE THE WET RAT	

Large portions of DNA can also be involved in a mutation. A piece of an individual chromosome containing one or more genes can be deleted or moved to a different location on the chromosome, or even to a different chromosome. Such rearrangements of the chromosome often have drastic effects on the expression of these genes.

Connection to In 1991, a new kind of mutation was discovered that involves an increase in the number of copies of repeated codons, called tandem repeats. The increase in repeated sequences seems to be involved in a number of inherited disorders. The first known example was fragile X syndrome—a syndrome that results in a number of mental and behavioral impairments. Near the end of a normal X chromosome, there is a section of CGG codons that repeat about 30 times. Individuals with fragile X have CGG codons that repeat hundreds of times. The syndrome received its name because the repeated area on the tip of the X chromosomes appears as a fragile piece hanging off the X chromosome, as illustrated in **Figure 21.** Currently, the mechanism by which the repeats expand from generation to generation is not known.

Reading Check **Describe** three types of mutations.

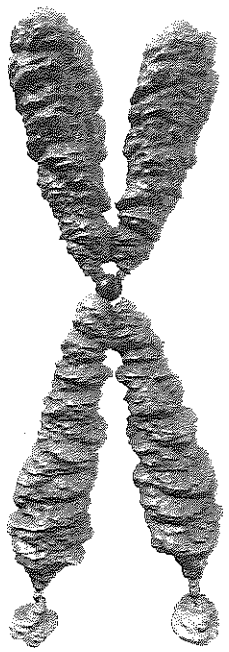
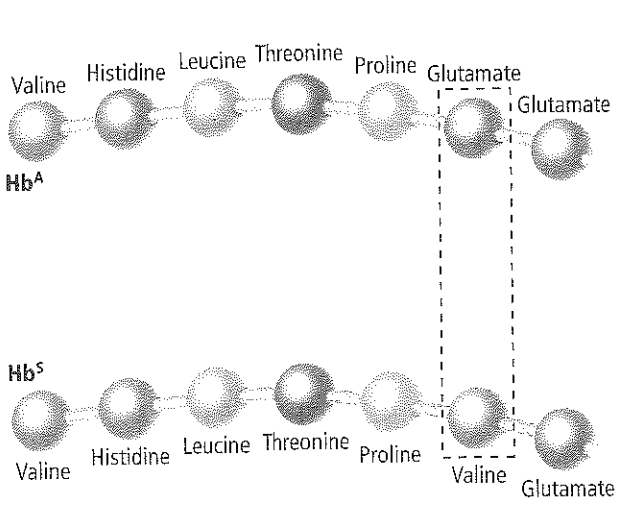


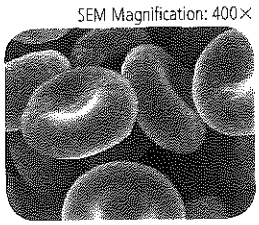
Figure 21 Fragile X syndrome is due to many extra repeated CGG units near the end of the X chromosome, making the lower tip of the X chromosome appear fragile.

Protein folding and stability You might expect that large changes in the DNA code, such as frameshift mutations or changes in position, lead to genetic disorders. However, small changes like substitutions also can lead to genetic disorders. The change of one amino acid for another can change the sequence of amino acids in a protein enough to change both the folding and stability of the protein, as illustrated in **Figure 22.**

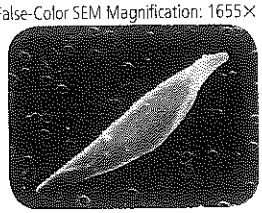
An example of a genetic disorder caused by a single point mutation is sickle-cell disease. In the case of sickle-cell disease, the codon for a glutamic acid (GAA) has been changed to a valine (GUA) in the protein. This change in composition changes the structure of hemoglobin and is the cause of this disorder.

Figure 22 A single amino acid substitution can cause the genetic disorder sickle-cell disease. **Recall** *what happens to the protein with the substituted amino acid.*





Normal shape of red blood cell



Sickle shape of red blood cell

Hemoglobin is made of four polypeptide chains, which are two sets of two identical chains. The molecule also contains a large carbon-ring structure that binds iron called the heme group. The substituted glutamic acid is located near the start of one set of chains, as shown in **Figure 22.** Glutamic acid is a polar amino acid, but the valine that substitutes for it in sickle-cell disease is nonpolar. Because of the charge difference, the sickle-cell hemoglobin folds differently than normal hemoglobin. The abnormal folding of the protein caused by the mutation results in a change to the sickle shape of the red blood cell. Numerous other diseases involve problems with protein folding, including Alzheimer's disease, cystic fibrosis, diabetes, and cancer.

Causes of mutation Some mutations, especially point mutations, can occur spontaneously. During replication, DNA polymerase sometimes adds the wrong nucleotides. Because the DNA polymerase has a proofreading function, the wrong nucleotide gets added only for one in one hundred thousand bases; it goes unfixed in less than one in one billion.

Certain chemicals and radiation also can damage DNA. Substances which cause mutations are called **mutagens** (MYEW tuh junz). Many different chemicals have been classified as mutagens. Some of these chemicals affect DNA by changing the chemical structure of the bases. Often these changes cause bases to mispair, or bond, with the wrong base. Other chemical mutagens have chemical structures that resemble nucleotides so closely that they can substitute for them. Once these imposter bases are incorporated into the DNA, it can not replicate properly. This type of chemical has become useful medically, especially in the treatment of HIV–the virus that causes AIDS. Many drugs used to treat HIV and other viral infections mimic various nucleotides. Once the drug is incorporated in the viral DNA, the DNA cannot copy itself properly.

VOCABULARY

WORD ORIGIN

Mutagen
comes from the Latin word *mutare,* meaning *to change* and from the Greek word *genes,* meaning *born*

DATA ANALYSIS LAB 2

Based on Real Data*

Interpret the Graph

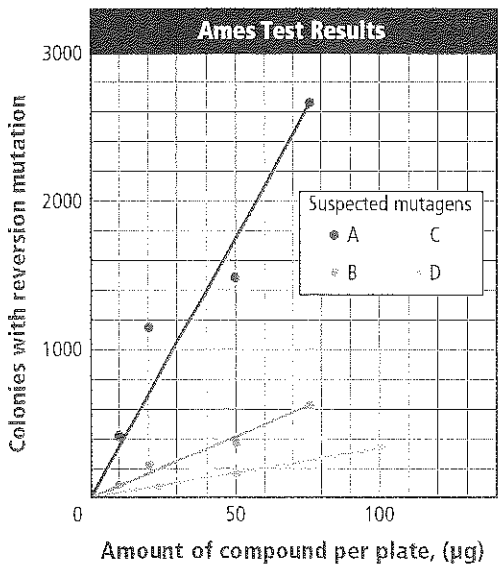
How can we know if a compound is a mutagen? The Ames test is used to identify mutagens. The test uses a strain of bacteria that cannot make the amino acid histidine. The bacteria are exposed to a suspected mutagen and grow on a medium without histidine. The bacteria that grow have a mutation called a reversion because they reverted to the natural condition of making histidine. The compounds in the graph were Ames tested.

Think Critically

1. **Describe** the relationship between the amount of the compound and the mutation.
2. **Analyze** which compound is the strongest mutagenic compound.

*Data obtained from: Ames. B.N. 1979. Identifying environmental chemicals causing mutations and cancer. *Science.* 204: 587-593

Data and Observations



High-energy forms of radiation, such as X-rays and gamma rays, are highly mutagenic. When the radiation reaches the DNA, electrons absorb the energy. The electrons can escape their atom, leaving behind a free radical. Free radicals are charged atoms with unpaired electrons that react violently with other molecules, including DNA. Ultraviolet (UV) radiation from the Sun contains less energy than X-ray radiation and does not cause electrons to be ejected from the atoms. However, UV radiation can cause adjacent thymine bases to bind to each other, disrupting the structure of DNA, as shown in **Figure 23.** DNA with this structure disruption, or kink, are unable to replicate properly unless repaired.

Body-cell v. sex-cell mutation When a mutation in a body cell, also called a somatic cell, escapes the repair mechanism, it becomes part of the genetic sequence in that cell and in future daughter cells. Somatic cell mutations are not passed on to the next generation. In some cases, the mutations do not cause problems for the cell. They could be sequences not used by the adult cell when the mutation occurred, the mutation might have occurred in an exon, or the mutation might not have changed the amino acid for which it was coded. These mutations are called neutral mutations. When the mutation results in the production of an abnormal protein, the cell might not be able to perform its normal function, and cell death might occur. Recall that mutations in body cells that cause the cell cycle to be unregulated can lead to cancer. All of these effects are contained within the cells of the organism as long as only body cells are affected.

When mutations occur in sex cells, also called germ-line cells, the mutations are passed on to the organism's offspring and will be present in every cell of the offspring. In many cases, these mutations do not affect the function of cells in the organism, though they might affect the offspring drastically. When the mutations result in an abnormal protein in the sex cell, the offspring is impacted. However, the offspring is not impacted when an abnormal protein is produced in an isolated body cell.

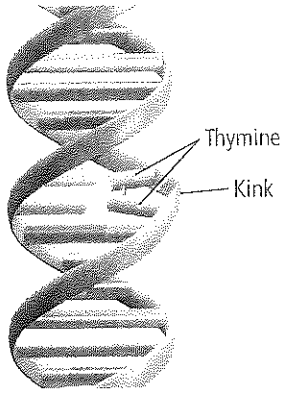


Figure 23 Ultraviolet radiation can cause adjacent thymines to bind to each other instead of to their complementary bases, making the DNA "kink" and preventing replication.

Section 4 Assessment

Section Summary

- Prokaryotic cells regulate their protein synthesis through a set of genes called operons.
- Eukaryotic cells regulate their protein synthesis using various transcription factors, eukaryotic nucleosome structures, and RNA interference.
- Mutations range from point mutations to the deletion or movement of large sections of the chromosome.
- Mutagens, such as chemicals and radiation, can cause mutations.

Understand Main Ideas

1. **Relate** gene regulation and mutations.
2. **Identify** the two main types of mutagens.
3. **Diagram** how adding lactose to a culture affects the lac operon of E. coli.
4. **Analyze** how a point mutation can affect the overall protein shape and function, using hemoglobin as an example.
5. **Compare and contrast** prokaryotic and eukaryotic gene regulation.

Think Critically

6. **Explain** why most mutations in eukaryotes are recessive.
7. **Hypothesize** why DNA replication has such accuracy.

WRITING in Biology

8. Write an article describing how Hox genes regulate development in animals.

Online Quiz

Biology & Society

Who owns genes?

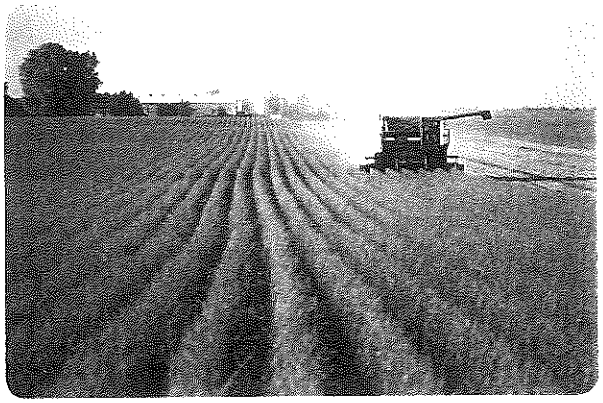
Can a company own parts of the human body? That is an ethical debate that has raged since 1977, when universities and private companies first started seeking patents on genes. To date, about 20 percent of all human genes have been patented. This issue has made headlines since a company patented the BRCA1 and BRCA2 genes, mutations of which have been linked to breast cancer and ovarian cancer.

Agricultural gene patents have also sparked fierce debate. In recent decades, companies have modified the genes in many plants to incorporate them with desirable traits, such as resistance to diseases and pests. Companies have received patents on these modified plant genes.

What is a patent? A patent grants the exclusive right to make a profit from the sale of an invention. Often, people or businesses have invested years and large amounts of money researching and developing an invention. The profits they receive from holding patents help them recoup their investments, as well as provide money for future research.

A patent on nature Opponents argue that patenting genes will hinder free and open scientific research and will harm patients seeking medical care. If companies own patents on genes, they can refuse to allow other scientists to use the genes in their work, possibly preventing important discoveries. The high cost of genetic testing and therapies related to patented genes can deter patients from receiving treatments.

Agricultural implications Agricultural gene patents pose an additional problem for farmers. If winds or animals bring seeds containing patented genes to the fields of a farmer who has not bought the rights to use those seeds, the company who holds the patent can sue the farmer. In the past, farmers have lost these court cases, even though it is impossible to stop natural forces from transferring seeds.



Soybeans

Corn

Around the world, the amount of land devoted to the cultivation of genetically modified plants is rising. Soybeans and corn are two crops that are often genetically modified.

As companies continue to seek patents on genes, the debate is certain to continue. For now, the patenting of genes is legal. But in the future, ethical and practical considerations might swing the pendulum the other way.

CURRENT Biology

Research Have students further research the issue of gene patenting. Divide the class into two teams, one for gene patenting and one against it and stage a debate.

(t)Jamey Stillings/Getty Images; (b)Bob Nichols, USDA-ARS

WebQuest

BIOLAB

FORENSICS: HOW IS DNA EXTRACTED?

Background: **DNA tests are important for biologists, doctors, and even detectives. Imagine that you are working in a lab where someone has brought a sample of corn from a crime scene to be analyzed. You decide to test the DNA of the corn to look for genes to identify the type of corn. Before the DNA sequence can be examined, the DNA must be extracted.**

Question: *How can DNA be extracted?*

Materials

corn kernels (50 g)
beakers (2)
blender
cheesecloth (4 squares–30 cm on each edge)
rubber band
glass spooling hook
homogenization medium (100–150 mL)
plastic centrifuge tube (30–50 mL)
contact lens cleaning tablet (containing papain)
95% ethanol (12 mL)
distilled water (3 mL)
test tube
container of ice
water bath at 60°C
stirring rod
timer or clock

Safety Precautions

Procedure

1. Read and complete the lab safety form.
2. Carefully weigh out 50 g of corn kernels.
3. Place the corn kernels into a beaker and cover with homogenization medium that has been warmed to 60°C. Place the beaker in a 60°C water bath for 10 min. Gently stir every 45 s.
4. Remove the beaker from the water bath and chill quickly in an ice bath for 5 min.
5. Pour the mixture into a blender and homogenize, or blend, to achieve a consistent texture.
6. Filter the homogenized mixture through four layers of cheesecloth into a clean large beaker on ice.
7. Pour 15 mL of the filtrate into a 30–50 mL plastic centrifuge tube.
8. Dissolve one contact lens cleaning tablet in 3 mL of distilled water in a test tube. Add this to the filtrate tube and mix gently.
9. Hold the filtrate tube at an angle and slowly pour 12 mL of cold 95% ethanol down the side of the tube.
10. Observe the DNA rising into the alcohol layer as a cloudy suspension of white strings. Use a hooked glass rod to spool the DNA, and allow it to dry.
11. **Cleanup and Disposal** Clean your lab area, disposing of chemicals and materials as directed by your teacher. Be sure to wash your hands when you are finished.

Analyze and Conclude

1. **Describe** the appearance of the DNA in suspension and once it has dried.
2. **Explain** why you put the corn kernels into the blender.
3. **Think Critically** Why is it important not to contaminate a sample of DNA that is to be sequenced? How would you know if you had contaminated your sample?

WRITING in Biology

Report Imagine you are the first researcher to extract DNA from corn. Write a report detailing your methods and possible applications of your discovery.

William Fritsch/Brand X Pictures

Chapter 12 Study Guide

THEME FOCUS Stability and Change Mutations within DNA can be passed on to future generations.

BIG Idea DNA is the genetic material that contains a code for proteins.

Section 1 DNA: The Genetic Material

double helix (p. 330)
nucleosome (p. 332)

KEY Idea The discovery that DNA is the genetic code involved many experiments.

- Griffith's bacterial experiment and Avery's explanation first indicated that DNA is the genetic material.
- The Hershey-Chase experiment provided evidence that DNA is the genetic material of viruses.
- Chargaff's rule states that in DNA the amount of cytosine equals the amount of guanine and the amount of thymine equals the amount of adenine.
- The work of Watson, Crick, Franklin, and Wilkins provided evidence of the double-helix structure of DNA.

Section 2 Replication of DNA

semiconservative replication (p. 333)
DNA polymerase (p. 334)
Okazaki fragment (p. 334)

KEY Idea DNA replicates by making a strand that is complementary to each original strand.

- The enzymes DNA helicase, RNA primase, DNA polymerase, and DNA ligase are involved in DNA replication.
- The leading strand is synthesized continuously, but the lagging strand is synthesized discontinously, forming Okazaki fragments.
- Prokaryotic DNA opens at a single origin of replication, whereas eukaryotic DNA has multiple areas of replication.

Section 3 DNA, RNA, and Protein

RNA (p. 336)
messenger RNA (p. 336)
ribosomal RNA (p. 336)
transfer RNA (p. 336)
transcription (p. 337)
RNA polymerase (p. 337)
intron (p. 337)
exon (p. 337)
codon (p. 338)
translation (p. 338)

KEY Idea DNA codes for RNA, which guides protein synthesis.

- Three major types of RNA are involved in protein synthesis: mRNA, tRNA, and rRNA.
- The synthesis of the mRNA from the template DNA is called transcription.
- Translation is the process through which the mRNA attaches to the ribosome and a protein is assembled.
- In eukaryotes, mRNA contains introns that are excised before leaving the nucleus. A cap and poly-A tail are added to the mRNA.
- One gene codes for one polypeptide.

Section 4 Gene Regulation and Mutation

gene regulation (p. 342)
operon (p. 342)
mutation (p. 345)
mutagen (p. 348)

KEY Idea Gene expression is regulated by the cell, and mutations can affect this expression.

- Prokaryotic cells regulate their protein synthesis through a set of genes called operons.
- Eukaryotic cells regulate their protein synthesis using various transcription factors, eukaryotic nucleosome structures, and RNA interference.
- Mutations range from point mutations to the deletion or movement of large sections of the chromosome.
- Mutagens, such as chemicals and radiation, can cause mutations.

Vocabulary eGames

Chapter 12 Assessment

Section 1

Vocabulary Review

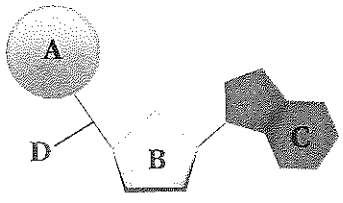
Each of the following sentences is false. Make the sentence true by replacing the underlined word with the correct vocabulary term from the Study Guide page.

1. The twisted ladder shape of DNA is called a nucleotide
2. A double helix consists of DNA wrapped around the histone proteins.

Understand Main Ideas

3. What are the basic building blocks of DNA and RNA?
   - **A.** ribose
   - **B.** purines
   - **C.** nucleotides
   - **D.** phosphorus
4. If a section of DNA has 27 percent thymine, how much cytosine will it have?
   - **A.** 23 percent
   - **B.** 27 percent
   - **C.** 46 percent
   - **D** 54 percent
5. Which was a conclusion of Griffith's work with *Streptococcus pneumoniae*?
   - **A.** DNA is the genetic material in viruses.
   - **B.** The structure of DNA is a double helix.
   - **C.** Bacteria exposed to DNA can incorporate the DNA and change phenotype.
   - **D.** The amount of thymine equals the amount of adenine in DNA.

Refer to the figure below to answer questions 6 and 7.

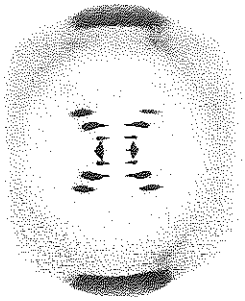


6. What is the entire labeled structure called?
   - **A.** nucleotide
   - **B.** RNA
   - **C.** base
   - **D.** phosphate
7. Which label represents the coding part of DNA?
   - **A.** A
   - **B.** B
   - **C.** C
   - **D.** D

Constructed Response

8. **Short Answer** Explain how DNA forms chromosomes in eukaryotic cells.

Use the figure below to answer question 9.



9. **Summarize** the experiments and data shown in the photo that led to the discovery of DNA.

Think Critically

10. **Design** How might you use radioactive phosphorus to demonstrate that the transforming compound of bacteria in Griffith's experiment was DNA?
11. **THINK** How would the results of the Hershey-Chase experiment have been different if protein were the genetic material?

Section 2

Vocabulary Review

Write a sentence defining each of the following vocabulary terms.

12. DNA polymerase
13. semiconservative replication
14. Okazaki fragment

Understand Main Ideas

15. With what does the synthesis of a new strand of DNA begin?
   - **A.** RNA primer
   - **B.** nucleotide unit
   - **C.** messenger RNA
   - **D.** transfer RNA

Chapter 12 Assessment

16. Which is true about the elongation of the lagging strand?
   A. does not require a template strand
   B. produces Okazaki fragments
   C. requires the action of RNA ligase
   D. proceeds by continually adding nucleotides to the 3' end

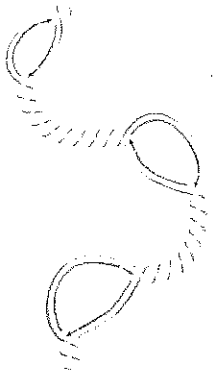
Constructed Response

17. **Short Answer** List the enzymes involved in replication and describe their functions.

18. Summarize the process of DNA replication in a diagram. Add labels to explain what is happening.

Think Critically

Use the figure below to answer questions 19 and 20.



19. **Determine** Imagine that you are a scientist looking at a cell through a microscope. You see DNA replicating in several areas. Determine what type of cell you are looking at based on the origins of replication.

20. **Hypothesize** why it is important for the DNA in the figure to have multiple origins of replication.

21. **Infer** how complementary base pairing is responsible for semiconservative replication.

Section 3

Vocabulary Review

Write a sentence that connects the vocabulary terms in each pair.

22. mRNA – tRNA

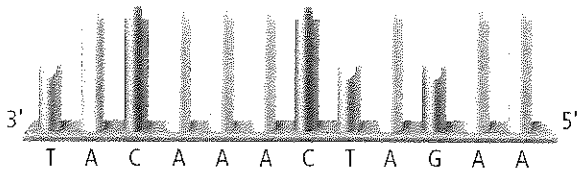
23. codon – RNA polymerase

24. intron – exon

Understand Main Ideas

25. Which correctly lists the changes to eukaryotic pre-mRNA to form mRNA?
   A. cap added, introns excised, and poly T tail added
   B. cap added, exons excised, and poly T tail added
   C. cap added, introns excised, and poly A tail added
   D. cap added, exons excised, and poly A tail added

Use the figure below to answer questions 26 and 27.



26. What is the mRNA sequence for the template strand DNA sequence in the figure?
   A. 5' ATGTTTGATCTT 3'
   B. 5' AUGUUUGAUCUU 3'
   C. 5' TACAAACTAGAA 3'
   D. 5' UACAAACUAGAA 3'

27. What is the sequence for the nontemplate strand of the DNA in the figure?
   A. 5' ATGTTTGATCTT 3'
   B. 5' AUGUUUGAUCUU 3'
   C. 5' TACAAACTAGAA 3'
   D. 5' UACAAACUAGAA 3'

Constructed Response

28. **Short Answer** Compare and contrast transcription and translation. Indicate where they occur in prokaryotic cells and eukaryotic cells.

29. Describe the experiment that led to the One Gene-One Enzyme hypothesis.

Think Critically

30. **Identify** the mRNA sequence and orientation if the nontemplate strand has the sequence 5' ATGCCAGTCATC 3'. Use **Figure 14** to determine the amino acid sequence coded by the mRNA.

Online Test Practice

Section 4

Vocabulary Review

Write the vocabulary term from the Study Guide page that describes each of the following processes.

31. regulation of a prokaryotic genome

32. control of the functional units of DNA

33. changes in DNA sequence

Understand Main Ideas

34. Which demonstrates an insertion mutation of the sequence 5' GGGCCCAAA 3'?
   - A. 5' GGGGCCAAA 3'
   - B. 5' GGGCCAAA 3'
   - C. 5' GGGAAACCC 3'
   - D. 5' GGGCCCAAAAAA 3'

35. Which is true about eukaryotic gene regulation?
   - A. Eukaryotic gene regulation is exactly like prokaryotic gene regulation.
   - B. Replication factors guide the binding of eukaryotic RNA polymerase to the promoter.
   - C. Activator proteins fold DNA to enhancer sites that increase the rate of gene transmission.
   - D. Repressor proteins bind to activators, preventing them from binding to the DNA.

36. Which is not a type of mutation?
   - A. base substitutions
   - B. insertions
   - C. RNA interference
   - D. translocation

Constructed Response

37. **Short Answer** Illustrate the effect of adding tryptophan to a culture of *E. coli.*

38. **Short Answer** Describe RNA interference.

Think Critically

39. **Infer** why base substitutions in the third position are least likely to cause a change in the amino acid for which it coded.

40. Hypothesize how it might be possible for bacteria to respond to environmental stress by increasing the rate of mutations during cell division.

Summative Assessment

41. Explain the central dogma of protein synthesis.

42. **Biology** The discovery of DNA and its structure required many scientists to research, conduct experiments, and publish their findings. Write about a scientific event that required scientists to build on others' findings to produce results.

43. **Biology** The book *Jurassic Park* by Michael Crichton presents the idea of isolating DNA from extinct organisms and "resurrecting" them. If this were possible, should this be done? Defend your opinion in an essay.

Document-Based Questions

Data obtained from: Watson, J.D. and Crick, F.H., 1953. Molecular Structure of Nucleic Acids. *Nature* 171: 737-738.

The following excerpts are from Watson and Crick's description of the structure of DNA.

"The novel feature of the structure is the manner in which the two chains are held together by the purine and pyrimidine bases. The planes of the bases are perpendicular to the fibre axis. They are joined together in pairs, a single base from one chain being hydrogen-bonded to a single base from the other chain so that the two lie side by side with identical z-co-ordinates. One of the pair must be a purine and the other a pyrimidine for bonding to occur."

"It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material."

44. Draw a diagram of DNA structure based on the description above.

45. According to the description, how are the bases joined together?

46. What did Watson and Crick see as a possible copying mechanism?

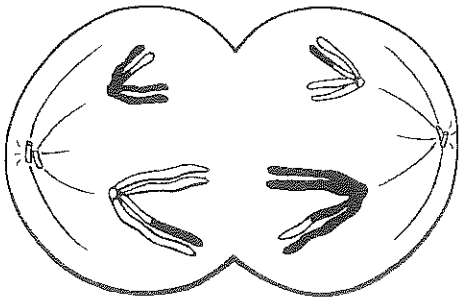
Standardized Test Practice

Cumulative

Multiple Choice

1. Which macromolecule can be formed using the sugars produced by plants during photosynthesis?
   - A. cellulose
   - B. DNA
   - C. lipid
   - D. protein

Use the diagram below to answer questions 2 and 3.

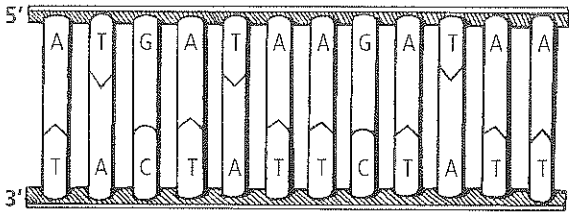


2. Which stage of meiosis is represented in the diagram?
   - A. anaphase I
   - B. anaphase II
   - C. metaphase I
   - D. metaphase II

3. Which process can take place during the stage of meiosis that follows the stage in the diagram?
   - A. change to diploid
   - B. crossing over
   - C. cytokinesis
   - D. DNA replication

4. What enzyme is responsible for "unzipping" the DNA strand during replication?
   - A. DNA helicase
   - B. DNA ligase
   - C. DNA polymerase
   - D. RNA primase

Use the illustration below to answer question 5.



5. Which sequence is possible for mRNA formed from the DNA strand shown in the illustration?
   - A. 5'AATAGAATAGTA3'
   - B. 5'AAUAGAAUAGUA3'
   - C. 5'ATGATAAGATAA3'
   - D. 5'AUGAUAAGAUAA3'

6. Which cells would likely undergo apoptosis?
   - A. cells between fingers
   - B. cells reproducing normally
   - C. cells reproducing slowly
   - D. cells surrounding the heart

7. Which genotype could be the one of a person whose blood type is A?
   - A. I^BI^B
   - B. *ii*
   - C. I^Ai
   - D. I^AI^B

8. Which sex chromosomes are present in a person with Kleinfelter Syndrome?
   - A. OY
   - B. XO
   - C. XXY
   - D. XYY

Short Answer

9. Using the law of independent assortment, describe a dihybrid cross of heterozygous yellow, round-seed pea plants (YyRr). Include a Punnett square and phenotype ratios in your response.

10. Give an example of a technological development, and explain how it contributed to scientists' understanding of the structure of DNA.

11. Which probably causes the coat color variations that occur only in the females of a certain animal? Give a reason to support your conclusion.

12. Suppose you perform a dihybrid cross between two organisms with the genotype RrYy. What percentage of the offspring would be homozygous for both traits? Explain how you determined the answer.

13. Why do you think Mendel's work preceded the search for molecules involved in inheritance?

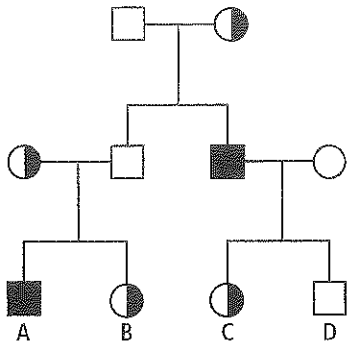
14. Suppose an organism (with a chromosome number of $2n = 6$) has monosomy of chromosome 3. How many chromosomes are in the organism's karyotype? Explain your answer.

15. Explain why the number of bases in a strand of mRNA can be different from the number in the DNA from which it was synthesized.

16. Explain why a hypothesis must be testable.

Extended Response

Use the figure below to answer question 17.



17. Describe the pattern of inheritance of the disease tracked in the pedigree above.

18. Human nerve cells seldom divide after they are formed. Evaluate how this might affect a person with a spinal cord injury.

19. Explain the role that publication of findings had in the discovery of DNA's structure.

Essay Question

For certain kinds of research studies, scientists recruit pairs of twins to be participants or subjects of the research. They might recruit identical or fraternal twins, depending on the focus of the study. Twins can be particularly helpful in studies about genetics and heredity.

Using the information in the paragraph above, answer the following question in essay format.

20. Imagine you are a research scientist. Write a plan for a research study that would require participants to be twins. Explain what you are trying to learn, whether you are looking for identical or fraternal twins, and why it is important to have twins as subjects for your study.

NEED EXTRA HELP?

If You Missed Question . . .	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Review Section . . .	8.2	10.1	10.1	12.2	12.3	9.3	11.2	11.3	11.2	12.2	11.2	10.2	12.2	11.3	11.2	12.3	11.1	9.1	12.1	11.2