

UNIT 6

The Structure and Function of DNA

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DNA is an essential molecule for all living things.

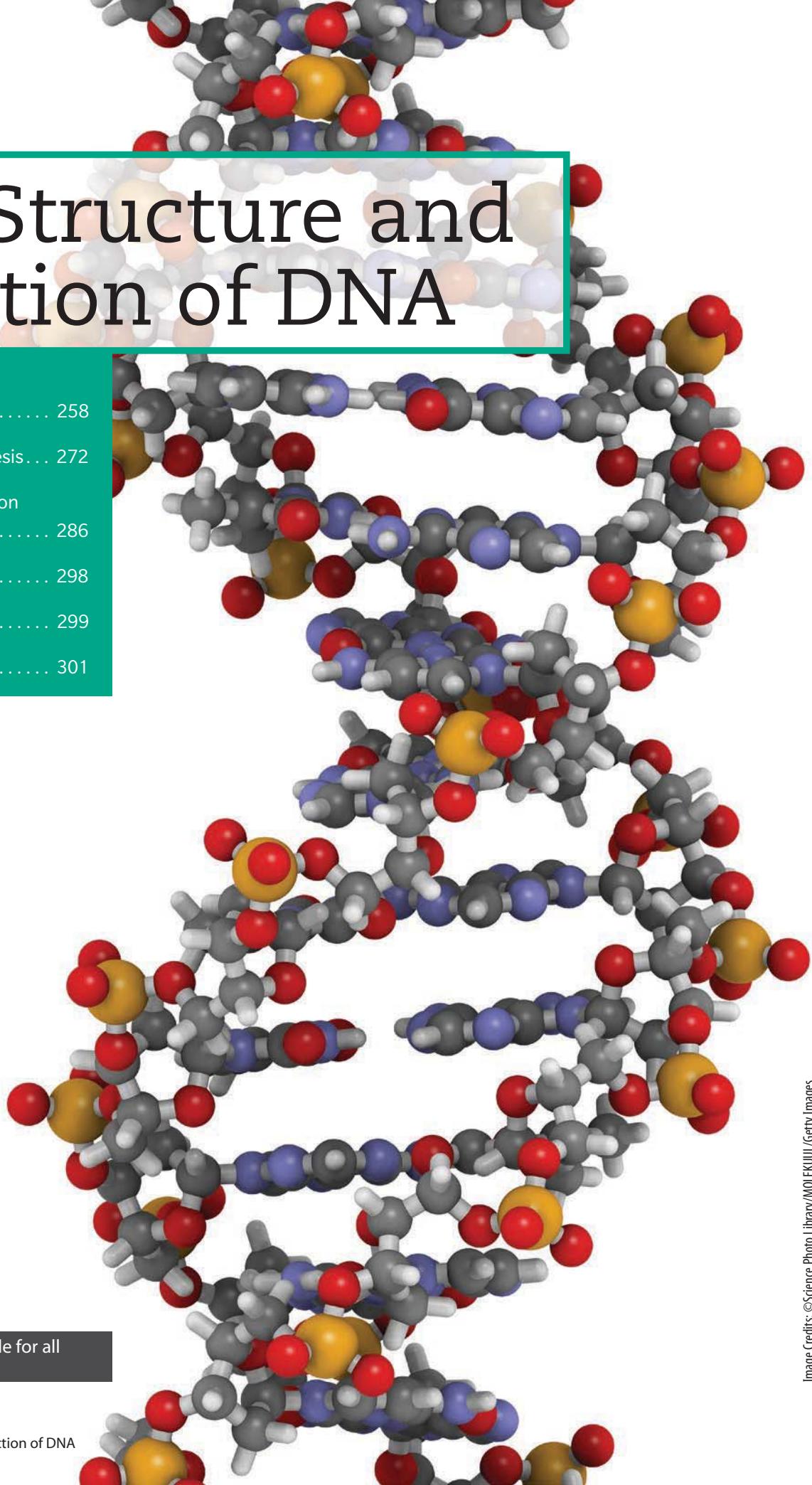


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FIGURE 1: Malformations in frogs may be linked to mistakes in the genetic code.



All living things use DNA to pass genetic information to the next generation. Genetic information directs the development and homeostasis of organisms through a process of translating the genetic code into proteins that have specific tasks. There are checks and balances built into the genetic system to ensure information is copied and interpreted properly. When the system malfunctions, it can result in disease, malformations, or even death. For example, some malformations in frogs can be linked to faulty genetic information. However, not all mutations have a negative effect. Alterations in DNA may be neutral or be beneficial to an organism. Over time, the mutation may lead to evolution of a population.



Predict How could altering the flow of information from DNA affect an organism?

DRIVING QUESTIONS

As you move through the unit, gather evidence to help you answer the following questions. In your Evidence Notebook, record what you already know about these topics and any questions you have about them.

1. How did scientists determine the structure of DNA?
2. How does the information in DNA get transferred into observable traits?
3. How is the flow of information from DNA regulated?

UNIT PROJECT

Case Study: Malformed Frogs

The malformation and decline of amphibians has been widely discussed since the 1990s, when hot spots of malformations in the United States were first brought to national attention. Scientific studies since then have linked the malformations and decline of frog populations to a number of factors. Combinations of these factors may cause the trends in malformations seen in frog populations. Research malformations in frogs and explore how DNA controls the structure, function, and regulation of proteins. Can you explain how genes and proteins are related to the trend of malformations in frogs?



Go online to download
the Unit Project
Worksheet to help you
plan your project.

DNA Structure and Replication

This baby goat literally gets its looks from its mother, thanks to cloned DNA.

 **Gather Evidence**
As you explore the lesson, gather evidence to explain how scientists determined the function and structure of DNA.

CAN YOU EXPLAIN IT?

How can you make conclusions about something you cannot see? This has been a challenge throughout the history of science. Sometimes scientists must use indirect evidence.

FIGURE 1: Each of these images shows a sample of DNA at a different level of detail.



Understanding the structure and function of DNA is one such case in biology. Early biologists recognized that characteristics were passed from one generation to the next, but the molecules responsible for this phenomenon were too small to be seen using early microscopes. Remarkably, biologists pieced together evidence about the structure of the molecule responsible for the unique characteristics of each organism. Over time, scientists built on the work of others, and, at the same time, technology continued to improve. Today, we have a much more clear understanding about DNA—the molecule that contains the code for life.



Predict Based on the images shown in Figure 1, how would you describe the appearance of DNA?

The Function of DNA

You are one of a kind and like no other—unless you are an identical twin, of course! How is it that you are so unique? You have a set of **traits**, or distinguishing characteristics, such as hair color, eye color, face shape, and body type, that are passed from one generation to the next. Early scientists made these same observations. But a question remained: How are traits passed from one generation to the next?



Analyze As you can see in Figure 2, humans have many observable traits that set us apart from each other. What are some traits you have?

FIGURE 2: Unique traits are observable among humans.



Codes for Proteins

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DNA, or deoxyribonucleic acid, is the molecule that stores the genetic information for all organisms. DNA is **heritable**, which means it can be passed from parent to offspring. This explains why offspring may look like their parents and why individual organisms within a species share many of the same characteristics. Scientists understood that traits were heritable long before they identified DNA and its key role in inheritance.

DNA does not act alone to pass on genetic information. The information from DNA is used to build another nucleic acid called RNA, or ribonucleic acid, and RNA in turn builds proteins. This concept is known as the **central dogma** of molecular biology. Recall that proteins play a crucial role in body functions. Enzymes help regulate chemical reactions. Other proteins provide structural support for cells. Proteins in the cell membrane transport nutrients across the membrane in response to changing conditions inside or outside the cell. Each protein has a unique structure and function in the cell, so proper coding is critical for building each protein.



Predict Kinesin is a motor protein that transports organelles and proteins around a cell. The structure of kinesin is crucial for its function. What might happen to the structure of kinesin if the DNA code was damaged?

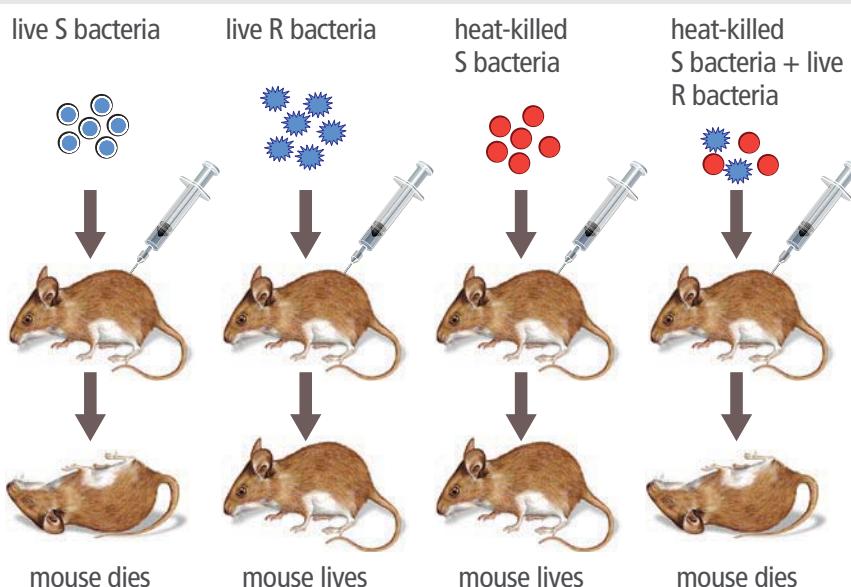
Mechanism for Heredity

Genetics is the study of biological inheritance patterns and variation in organisms. Gregor Mendel, an Austrian monk, was an early contributor to our understanding of genetics. Mendel's revolutionary experimentation with breeding pea plants identified factors that controlled traits. He correctly predicted that traits can be inherited as discrete units passed from parents to offspring. However, it would take the work of several different scientists over many years to discover DNA and explain how it codes for the inheritance of individual traits. Results from experiments led by these scientists supported the conclusion that DNA is the molecule of inheritance.

Griffith's Experiments

In 1928, the British microbiologist Frederick Griffith was investigating two types of pneumonia-causing bacteria. One type, called *S*, has a smooth outer coating made from carbohydrates. The other type, called *R*, has a rough outer surface. As shown in Figure 3, when Griffith injected mice with both types of bacteria, only the *S*-type killed the mice. When Griffith injected mice with heat-killed *S* bacteria, they were unaffected. However, when he injected the mice with a combination of heat-killed *S* bacteria and live *R* bacteria, the mice died. Even more surprising, he found live *S* bacteria in a blood sample taken from the dead mice. Unable to identify the factor that transformed harmless *R* bacteria into disease-causing *S* bacteria, Griffith called the mystery material the *transforming principle*. This mystery would be a question for other scientists to explore.

FIGURE 3: Griffith's Experimental Design



Collaborate With a partner, discuss what further questions you would ask based on Griffith's experimental results.



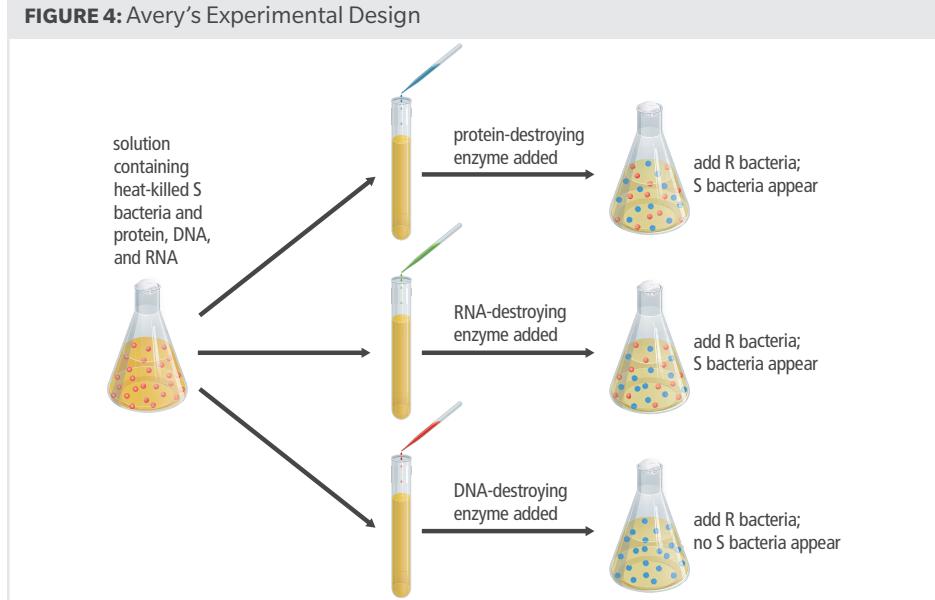
Analyze What evidence suggested that there is a transforming principle?

Avery's Experiments

Oswald Avery and his fellow scientists were intrigued by Griffith's transforming principle. Avery's team worked for more than 10 years to answer the question of what transformed the *R* strain. The scientists started with heat-killed *S* bacteria cells. They used a detergent to break down the bacteria, which resulted in an extract that contained only protein, DNA, and RNA molecules. Initial experiments showed that this extract contained the transforming principle.

Avery's team then used enzymes to break down each of the molecules separately. Once degraded, each sample was mixed with *R*-strain bacteria to test for transformation to *S*-strain. The results of this work are shown in Figure 4.

FIGURE 4: Avery's Experimental Design



Explain Why did Avery's group destroy each type of molecule before adding it to the solution containing R bacteria? What can you conclude from the results?

Avery and his group performed a chemical analysis of the molecule determined to be the “transforming principle.” The table in Figure 5 shows the percentage of nitrogen and phosphorus and the ratio of nitrogen to phosphorus for four samples.



Data Analysis

FIGURE 5: Chemical analysis of the transforming principle

	% Nitrogen (N)	% Phosphorus (P)	Ratio of N to P
Sample A	14.21	8.57	1.66
Sample B	15.93	9.09	1.75
Sample C	15.36	9.04	1.69
Sample D	13.40	8.45	1.58
Known value for DNA	15.32	9.05	1.69



Analyze How does the data in the table support the claim that DNA is the transforming principle?

Avery's group also performed standard chemical tests that showed DNA was present in the extract and protein was not. They also used enzymes to destroy different molecules such as lipids and carbohydrates. Each time a molecule was destroyed, the transformation from R to S bacteria still occurred—until they destroyed DNA. When DNA was destroyed, the transformation did not occur.

In 1944, Avery and his group presented the evidence to support their conclusion that DNA must be the transforming principle, or genetic material. However, the scientific community remained skeptical as to whether the genetic material in bacteria was the same as that in other organisms. Despite Avery's evidence, some scientists insisted that his extract must have contained protein. Further testing remained to be done.

Hershey and Chase Experiments

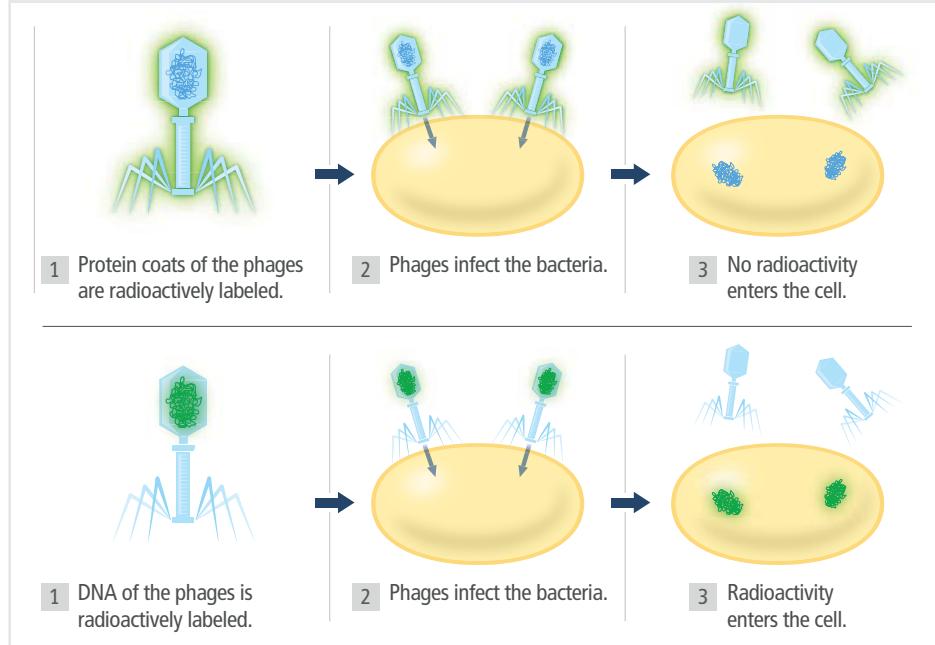
In 1952, two American biologists, Alfred Hershey and Martha Chase, were researching different viruses that infect bacteria. These viruses, called bacteriophages, are made up of a DNA core surrounded by a protein coat. To reproduce, the bacteriophages attach themselves to bacteria and then inject material inside the cell. Hershey and Chase thought up a clever procedure that used the chemical elements found in protein and DNA. Protein contains sulfur but very little phosphorus, while DNA contains phosphorus but no sulfur. The researchers grew phages in cultures that contained radioactive isotopes of sulfur or phosphorus. Hershey and Chase then used these radioactively tagged phages in two experiments.

In the first experiment, bacteria were infected with phages that had radioactive sulfur atoms in their protein molecules. Hershey and Chase then used a kitchen blender and a centrifuge to separate the bacteria from the parts of the phages that remained outside the bacteria. When they examined the bacteria, they found no significant radioactivity.

In the second experiment, Hershey and Chase repeated the procedure with phages that had DNA tagged with radioactive phosphorus. This time, radioactivity was clearly present inside the bacteria.

FIGURE 6: Hershey and Chase's Experimental Design

Analyze Why did the Hershey and Chase experiments support the idea that DNA is the transforming principle?



Explain

1. Draw a table to summarize each experiment. Include information on how the experiments relate to one another, key data, and questions that remained after each experiment.
2. Develop an argument for why the data from each experiment either supported or did not support the conclusion that DNA is the molecule of inheritance.
3. Scientists often build on, and improve, the work of other scientists. This process may cover a long period of time. Explain how advances in technology affect this process of building scientific knowledge.

The Structure of DNA

Once Hershey and Chase completed their experiments with bacteriophages, it was clear that DNA was responsible for the inheritance of traits. What scientists did not yet understand, however, was how DNA stored genetic information. To understand this, they first needed to understand the molecular structure of DNA.

Nucleotides

Scientists have known since the 1920s that the DNA molecule is a very long polymer, or chain of repeating subunits. The subunit, or monomer, that makes up DNA is called a **nucleotide**, shown in Figure 7.

One molecule of human DNA contains billions of nucleotides. However, if you were to divide all of those nucleotides into groups of identical nucleotides, you would end up with just four groups. The nucleotides that make up DNA differ only in their nitrogen-containing, or nitrogenous, bases. The bases are cytosine (C), thymine (T), adenine (A), and guanine (G). The letter abbreviations refer both to the bases and to the nucleotides that contain the bases.

FIGURE 8: The four nucleotides that make up DNA

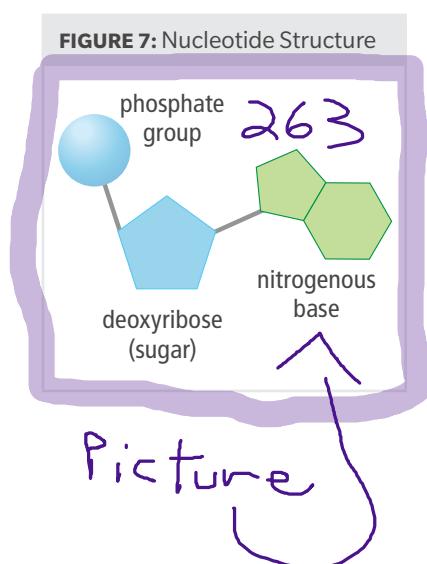
PYRIMIDINES			PURINES		
Name of base	Structural formula	Model	Name of base	Structural formula	Model
thymine			adenine		
cytosine			guanine		



Explain Use the information in Figure 8 to answer the following questions.

- How do the structures of purines differ from the structures of pyrimidines?
- Which base is most similar in structure to thymine?

FIGURE 7: Nucleotide Structure



Determining DNA Structure

For a long time, scientists assumed that DNA was made up of equal amounts of the four nucleotides and that the DNA in all organisms was therefore exactly the same. That assumption made it difficult to convince scientists that DNA was the genetic material. They reasoned that identical molecules could not carry different instructions across all organisms. However, in 1950, Erwin Chargaff conducted a set of experiments that challenged this assumption.

Chargaff's Experiments

Chargaff changed the thinking about DNA by analyzing the DNA of several different organisms. He found that the same four bases are found in the DNA of all organisms, but the proportion of the four bases differs from one organism to another.



Data Analysis

FIGURE 9: Nucleotide ratios leading to the formulation of Chargaff's rules

Source	Adenine to Guanine	Thymine to Cytosine	Adenine to Thymine	Guanine to Cytosine	Purines to Pyrimidines
Human	1.56	1.75	1.00	1.00	1.00
Chicken	1.45	1.29	1.06	0.91	0.99
Salmon	1.43	1.43	1.02	1.02	1.02
Wheat	1.22	1.18	1.00	0.97	0.99
Yeast	1.67	1.92	1.03	1.20	1.00
<i>E-coli</i> k2	1.05	0.95	1.09	0.99	1.00



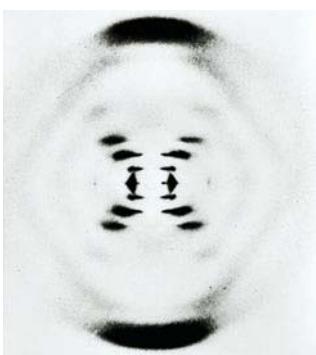
Analyze

1. The numbers shown in the table are ratios. For example, the ratio of adenine to guanine in humans is 1.56 to 1, or 1.56:1. The 1 is assumed, and not shown. What do you observe about these ratios?
2. How does Chargaff's work support the idea that DNA is the molecule of inheritance?

FIGURE 10: X-ray Evidence



a Rosalind Franklin



b X-ray crystallography

Franklin's X-Ray Crystallography

In the early 1950s, British scientist Rosalind Franklin was studying DNA using a technique called x-ray crystallography. When crystallized DNA is bombarded with x-rays, the atoms diffract the x-rays in a pattern that can be captured on film. Franklin's x-ray photographs of DNA showed an X surrounded by a circle. The pattern and angle of the X suggested that DNA consists of two strands, spaced at a consistent width apart and twisted into a helical shape.



Collaborate Rosalind Franklin's results made her think that the DNA molecule was a helical, or spiral, shape. With a partner, discuss what questions about the structure of DNA were not answered by her results.

Watson and Crick's Model of DNA

At about the same time that Franklin was working with x-ray crystallography, American geneticist James Watson and British physicist Francis Crick were also studying DNA structure. Their interest was sparked by the earlier work of Hershey, Chase, and Chargaff as well as biochemist Linus Pauling. Pauling discovered that the structure of some proteins was a helix, or spiral. Watson and Crick hypothesized that DNA might also be a helix. Franklin's crystallographs, along with her calculations, gave them the clues they needed to develop models like the one shown in Figure 11.

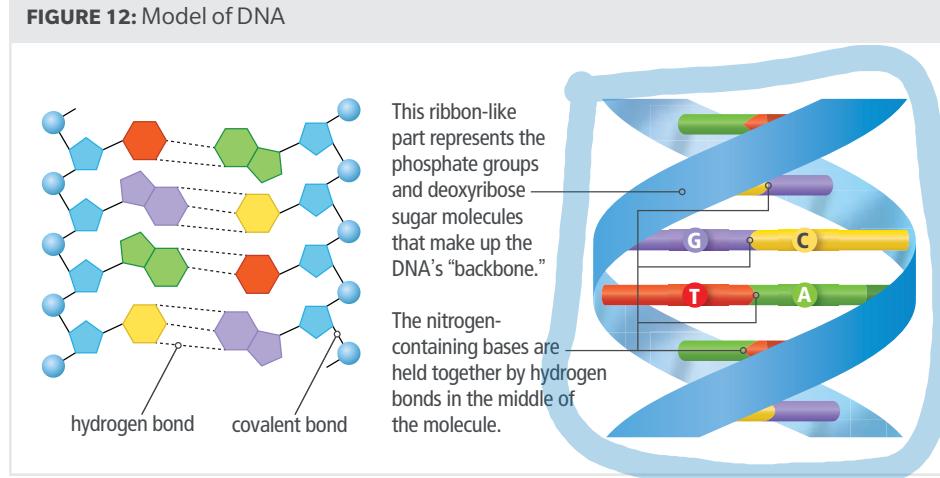
Watson and Crick began working with their model to determine the structure of DNA. They knew they had to be able to twist their model to account for the evidence provided by Franklin's x-rays. They placed the sugar-phosphate backbones on the outside and the nitrogenous bases on the inside. At first, Watson reasoned that A might pair with A, T with T, and so on. But the bases A and G are about twice as wide as C and T, so this made a helix that varied in width. This arrangement was not supported by Franklin's data, which showed that the width of the molecule was constant. Finally, Watson and Crick found that if they paired double-ringed nucleotides with single-ringed nucleotides, the bases fit like a puzzle.

In April 1953, Watson and Crick published their DNA model in the journal *Nature*. Working from Franklin's data, they built a double-helix model in which the two strands were complementary—that is, if one strand is ACACAC, the other strand is TGTGTG. The pairing of bases in their model supported Chargaff's results. These A-T and C-G relationships became known as Chargaff's rules.

Current DNA Model

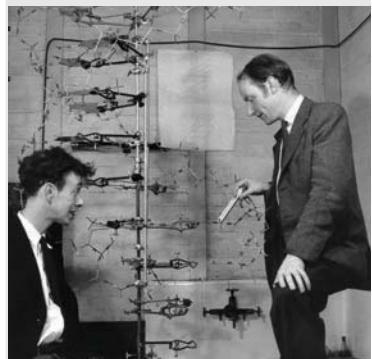
As technology has advanced, our understanding of DNA has continually improved. The current model represents DNA nucleotides of a single strand joined together by covalent bonds that connect the sugar of one nucleotide to the phosphate of the next nucleotide. The alternating sugars and phosphates form the sides of a double helix, or the sugar-phosphate backbone of the molecule. The DNA double helix is held together by hydrogen bonds between the bases in the middle. Individually, each hydrogen bond is weak, but together, they maintain DNA structure.

FIGURE 12: Model of DNA



As Watson and Crick's model showed, the bases of the two DNA strands always follow Chargaff's rules for base pairing: thymine (T) always pairs with adenine (A), and cytosine (C) always pairs with guanine (G). These pairings occur because of the sizes of the bases—a purine is always paired with a pyrimidine—and the ability of the bases to form hydrogen bonds with each other. As an example of base pairing, if a sequence of bases on one strand of DNA is CTGCTA, the matching DNA strand will be GACGAT.

FIGURE 11: James Watson (left) and Frances Crick (right) used a model to figure out the structure of DNA.



Analyze By building a physical model, Watson and Crick were able to see that adenine fit with thymine and guanine fit with cytosine. How do Chargaff's results support Watson and Crick's model?

Double
Helix
- twisted ladder
shape

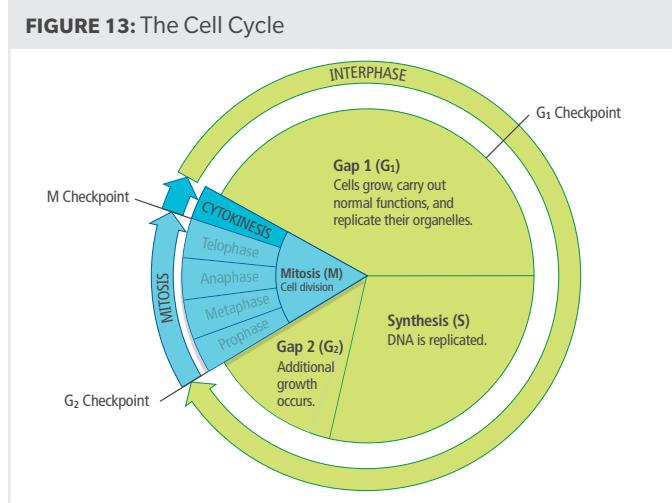
Predict Look at the hydrogen bonds between the base pairs in Figure 12. Which base pairs do you think are held more tightly together?

Pairs of
nitrogenous
bases in DNA
that form the
'rungs' of DNA
ladder.



Model Describe the structure of DNA using a ladder as an analogy. What makes up the rungs, or steps, of the ladder? What makes up the sides? How is the ladder shaped?

DNA Replication

FIGURE 13: The Cell Cycle

E **Explain** The word *synthesis* comes from a Greek word meaning “to put together, or combine.” Why is the S phase called the *synthesis phase*?

The process by which DNA is copied during the cell cycle is called **replication**. This process takes place in the nucleus during the S phase of the cell cycle. After the two strands of DNA are separated, each strand becomes a template for a new strand of DNA. The order of the bases is preserved, so DNA is replicated accurately each time. Replication ensures that every cell has a complete set of identical genetic information.

DNA Process for Replication

DNA stores genetic information; however, it does not copy itself. Enzymes and other proteins do the work of replication. Some enzymes start the process by breaking the weak hydrogen bonds that hold the base pairs together. This

“unzips” the DNA molecule into two separate strands. Other proteins hold the strands apart while each strand serves as a template. Nucleotides that are floating free in the nucleus can then pair up with the nucleotides of the templates on each strand of the separated DNA. A group of enzymes called **DNA polymerases** are involved in this process. **DNA polymerase** binds the new nucleotides together. When the process is finished, the result is two complete molecules of DNA, each exactly like the original double strand.

DNA Unzips

An enzyme called **helicase** binds to the DNA molecule and unzips the strands. This occurs at many places along the chromosome, called the *origins of replication*. The hydrogen bonds connecting base pairs are broken, the original molecule separates, and the bases on each strand are exposed. Other proteins, called stabilizing proteins, bind to and stabilize the separated strands. The process of unzipping DNA proceeds in two directions simultaneously, rather like unzipping a suitcase.

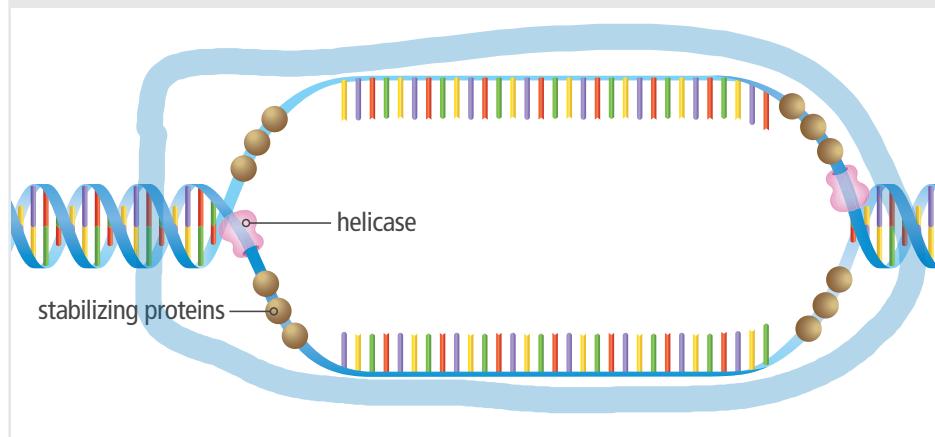
Structure and Function



The name of an enzyme can explain its function. The suffix *-ase* indicates that a protein is an enzyme. The root word before the suffix indicates which molecule is the substrate for this enzyme. One enzyme involved in DNA replication is called helicase.

FIGURE 14: DNA unzipping.

Explore Online

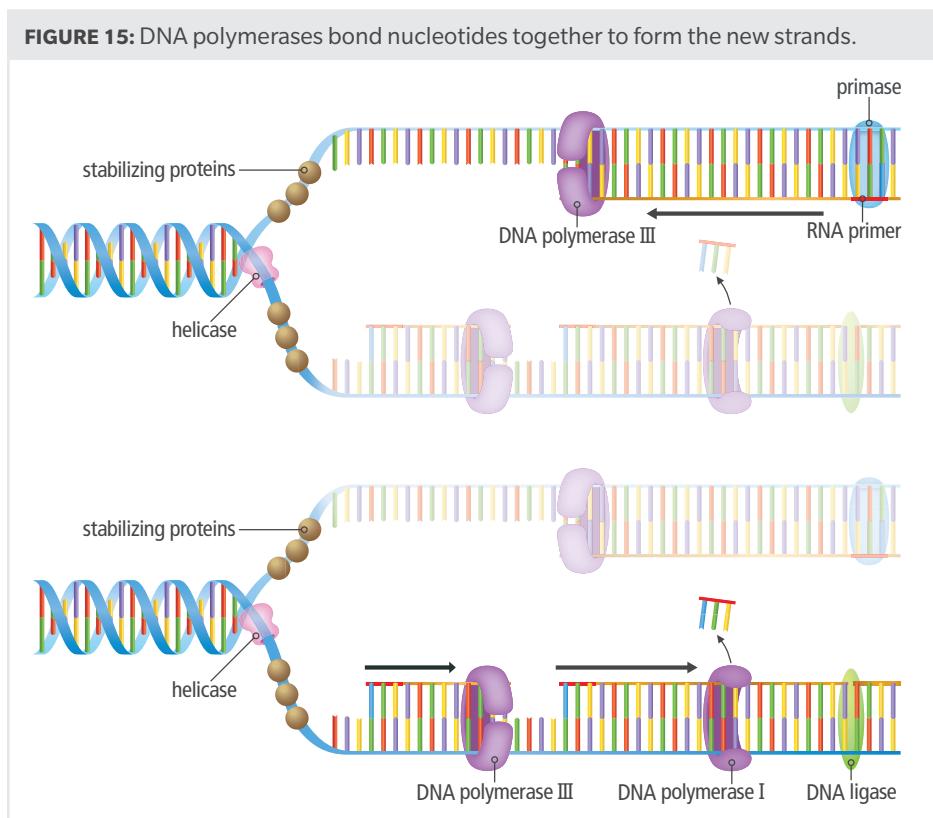


Nucleotide Pairing

Once the DNA is unzipped, the process of adding nucleotides to the single-stranded templates begins. An enzyme called *primase* makes an RNA primer, a short nucleotide segment that begins the synthesis process. The RNA primer segment is necessary because DNA polymerase can only add nucleotides to an existing strand.

Similar to the unzipping process, replication takes place at both forks simultaneously. One by one, free nucleotides pair with the bases exposed as the template strands unzip. Starting at the primer, DNA polymerases bond the nucleotides together and form new strands using DNA nucleotides that are complementary to each template. Because the two strands of the DNA molecule are positioned in opposite directions, there are differences in how each strand is copied. On the *leading strand*, highlighted in the top image in Figure 15, DNA replication begins at the primer and proceeds in one direction as *DNA polymerase III* adds new nucleotides. On the *lagging strand*, highlighted in the bottom image in Figure 15, replication occurs in a discontinuous, piece-by-piece way in the opposite direction. On the lagging strand, primers attach at multiple locations so multiple molecules of DNA polymerase III can add nucleotides to each primer at the same time.

FIGURE 15: DNA polymerases bond nucleotides together to form the new strands.



Once the open regions on both strands are filled in, an enzyme called *DNA polymerase I* removes the RNA primers from both strands and replaces them with DNA nucleotides. On the lagging strand, the fragments are then bound together by an enzyme called *ligase*.

When replication is complete, there are two identical molecules of DNA. Each molecule contains one strand of DNA from the original molecule and one new strand. This type of replication is called *semiconservative* because each new molecule of DNA conserves, or keeps unchanged, one strand of DNA from the original molecule.



Language Arts Connection

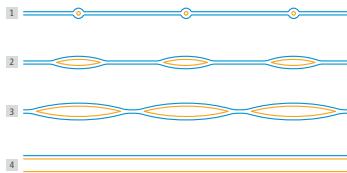
Use an analogy to explain the sequence of events in the replication of DNA. Cite evidence from the diagram to support your explanation.



Model Make a model of a DNA molecule to explain semiconservative replication.

Fast and Accurate Replication

FIGURE 16: Replication Origins



In every living thing, DNA replication happens repeatedly, and it happens remarkably fast. In human cells, about 50 nucleotides are added every second to a new strand of DNA at an origin of replication. But even at this rate, it would take many days to replicate a molecule of DNA if the molecule were like a jacket zipper, unzipping one tooth at a time. To speed the process along, replication takes place at hundreds of origins of replication along the DNA molecule. This allows replication to be completed in only a few hours rather than days.

For the most part, replication proceeds smoothly. Occasionally, though, the wrong nucleotide is added to the new strand of DNA. This is called a *base substitution*, which is a type of point mutation—a mutation that occurs at a single location in the sequence of nucleotides. However, DNA polymerase can detect the error, remove the incorrect nucleotide, and replace it with the correct one. In this way, errors in DNA replication are limited to about 1 error per 1 billion nucleotides. If the substitution is not repaired, it may permanently change the organism's DNA. Sickle-cell anemia is an example of a genetic disorder that results from a base-substitution point mutation.

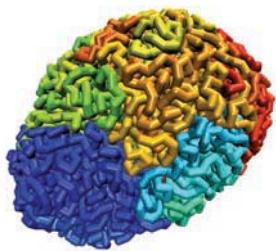


Predict Why is it important for DNA polymerase I to proofread the new strands of DNA before the cell divides?



Engineering

FIGURE 17: Folded DNA Model



The Art of DNA Folding

The human body has a knack for packing. It fits about eight meters of large and small intestines into the abdomen and jams about 100,000 kilometers of blood vessels, large and small, into the body. It should come as no surprise that the tiniest unit of the human body, the cell, has the same astonishing capability.

There are about 3 billion DNA base pairs in the human genome. If stretched out, the strand would be about 180 meters. This must fit into an area the size of a pinpoint. To make that happen, DNA must be tightly folded over and again, without becoming a tangled mess. The problem is solved by the formation of about 10,000 precise, non-overlapping loops like the ones in a bow. Instead of knots, the loops are held together by special proteins. The loops are crumpled to conserve space and are coated with chemical tags. The loops are then organized into groups by tag.



Explain How does the structure of DNA aid in its replication?



Hands-On Lab

Extracting DNA

While scientists use DNA extraction kits available from biotechnology companies, you can actually extract DNA using common ingredients found in your own home. During a DNA extraction, a detergent is used to burst open cells so that the DNA is released into solution. Then alcohol is added to the solution to cause the DNA to precipitate out. In this activity, you will extract DNA from a strawberry. Unlike human cells, which contain two copies of each chromosome, a strawberry has eight copies of each chromosome in its cells.



Predict What will DNA extracted from a strawberry look like?

FIGURE 18: Strawberries have eight copies of each chromosome in their cells.



PROCEDURE

1. Place the alcohol in a freezer 24 hours before beginning the lab.
2. Place the strawberry in a plastic zipper bag. Zip the bag closed.
3. Gently crush the strawberry by squeezing it inside the closed bag for 2 minutes.
4. Carefully open the bag and add 1 teaspoon water, 1 teaspoon liquid dish soap, and a pinch of salt. Zip the bag closed. Knead for 1 minute.
5. Pour the strawberry mixture into a cheesecloth-lined funnel that is set into a test tube to filter out the solids.
6. Remove the alcohol from the freezer. Open the test tube lid and tilt it in your hand. Very slowly, pour a small amount of alcohol down the inside of the test tube just until there is a thin layer floating on top of the solution.
7. Observe the test tube. You should see a band of white, gooey material forming just beneath the layer of alcohol. Gently put the skewer into the test tube and twirl it in the white material in one direction only. Wind the material around the skewer, then carefully draw it up and out of the test tube.
8. Record your observations.

ANALYZE



Explain Use your results from this activity to answer the following questions.

1. Describe the appearance of your DNA sample.
2. How is your DNA sample similar to and different from Watson and Crick's model?
3. The sample of DNA came from many strawberry cells. Do you think you would have been able to get the same result from your experiment if you had extracted DNA from a single cell?

MATERIALS

- cheesecloth
- funnel
- isopropyl alcohol (91%)
- dish soap, liquid
- salt
- strawberry (1 per student)
- teaspoon
- test tube with stopper
- water
- wood skewer
- zipper bag, plastic, quart size



Lesson Self-Check

CAN YOU EXPLAIN IT?

FIGURE 19: With advanced technology, we can directly observe DNA.



The photos shown here represent images of DNA at different scales. Current models of DNA include specific details about the shape and chemical makeup of this molecule. How do we know what DNA looks like if even our best technology to date gives us limited images?

What we know about DNA today is the result of multiple scientists building on each other's work. At each step in the process, scientists made observations, asked questions, tested ideas, and shared data. Advances in technology let scientists expand on discoveries, adding new information to our body of knowledge. For example, Frederick Griffith's discoveries led to questions Oswald Avery wanted to answer. Avery's work, in turn, provided valuable information that helped Alfred Hershey and Martha Chase prove definitively that DNA is the molecule of inheritance. James Watson and Francis Crick built on Erwin Chargaff's base-pairing rules and evidence from Linus Pauling to propose DNA's helical structure. The work of Rosalind Franklin was critical to the confirmation that DNA did indeed have a twisted, helical shape.



Explain Refer to the notes in your Evidence Notebook to explain how you would describe the structure of DNA. Use evidence and models to support your explanation, and address the following questions in your explanation:

1. How did the research of scientists such as Chargaff, Franklin, Watson, and Crick help advance our understanding of the structure of DNA?
2. What other methods can you think of that could be used to further study the structure of an object, such as DNA?

CHECKPOINTS

Check Your Understanding

1. What is the complementary DNA strand for a strand with the nucleotide sequence AACCCGGTTT?
 - a. GGAAATCCCT
 - b. TTAAACCGGG
 - c. TTGGGCCAAA
 - d. CCGGGTTAAT
2. What did Avery's work on the identification of transforming factors prove?
 - a. DNA is made of four different nucleotides.
 - b. The DNA molecule is a double-stranded helix.
 - c. Genetic information is contained in DNA.
 - d. Bacterial DNA is interchangeable between species.
3. Replication is a critical process during the cell cycle. In which phase of the cell cycle does replication take place?
 - a. G₁
 - b. G₂
 - c. S
 - d. M
4. What knowledge did scientists gain based on the x-ray crystallograph taken by Rosalind Franklin?
 - a. The sequence of nucleotides
 - b. How nucleotide bases form a template
 - c. The role of DNA in genetic mutations
 - d. The double-helix structure of DNA
5. How does the central dogma connect DNA, RNA, and proteins?
6. What do you predict would happen to the length of a human pregnancy if there was a single origin of replication on each chromosome?
7. What is the function of the proofreading step of replication? What might happen if this step were skipped?
8. What process did Watson and Crick use to develop their model of DNA, and how did it differ from the controlled experiments used by Griffith, Avery, and Hershey and Chase?

9. How do the base-pairing rules explain how a strand of DNA acts as a template during DNA replication?

MAKE YOUR OWN STUDY GUIDE



In your Evidence Notebook, design a study guide that supports the main idea from this lesson:

DNA codes for proteins and is responsible for an organism's traits.

Remember to include the following information in your study guide:

- Use examples that model main ideas.
- Record explanations for the phenomena you investigated.
- Use evidence to support your explanations. Your support can include drawings, data, graphs, laboratory conclusions, and other evidence recorded throughout the lesson.

Consider how the unique structure of DNA allows it to be copied and to transmit traits from parent to offspring.

Protein Synthesis

Like computers that use codes to do tasks, DNA uses codes to make proteins.

CAN YOU EXPLAIN IT?

FIGURE 1: In some ways, computer programming is similar to protein synthesis.



Gather Evidence

As you explore the lesson, gather evidence for how DNA code is translated into the language of proteins.

In order to use technology, humans often have to “talk to” computers. This requires special programming languages. Rather than using words to communicate, computers have their own language made up of 1s and 0s, which represent the states “on” and “off.” This language system is referred to as binary code. Programming languages help people translate between the person and the computer’s language.

Binary code uses only two values: 0 and 1. However, computers can be programmed to carry out millions of different tasks. DNA also uses a code, and it contains only four components, which are represented by the letters A, T, G, and C. However, using this “four-letter code” allows cells to produce thousands of different proteins.



Predict How do you think a code consisting of so few characters can encode the instructions for building thousands of different proteins?

Introduction to Protein Synthesis

You have learned that DNA determines traits and codes for proteins, but how does the language of DNA translate to the language of proteins? Protein synthesis is basically a two-step process in which information flows from DNA to RNA to proteins.

The Central Dogma

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Soon after discovering the structure of DNA, Francis Crick defined what he called the “central dogma” of molecular biology. Crick stated that information flowed from DNA to proteins, but not in the other direction. This flow of information from DNA to proteins is referred to as **protein synthesis**. Crick proposed that in the first step of this process, information flowed from DNA to an intermediate molecule of RNA. In the second step, information was transferred from the RNA to a protein molecule.

Recall that in addition to providing the template for protein synthesis, the DNA code can also be copied. Replication is the process during the cell cycle in which DNA is copied, so that when cell division occurs, each new cell receives a full set of DNA.



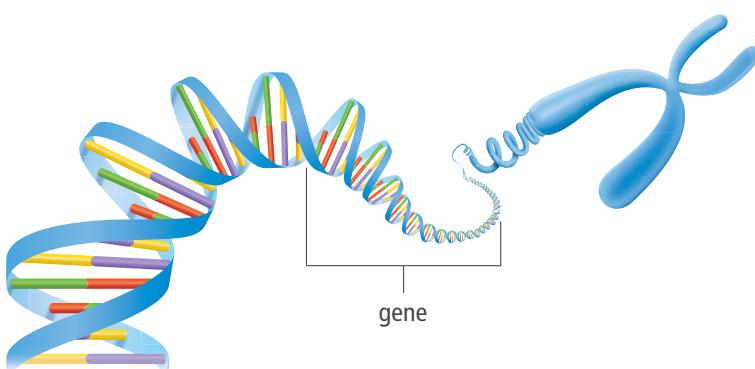
Model Create a flow chart to illustrate the flow of information in both protein synthesis and DNA replication.

Genes Code for Proteins

Each protein is coded for by a section of DNA called a gene. A gene is a piece of DNA that provides instructions for a cell to make a certain protein. Humans have around 19,000 protein-coding genes. However, the number of genes is not necessarily related to the complexity of the organism. For example, grape plants are fairly simple organisms, but they have over 30,000 genes according to the most recent count.

Genes are the most basic unit of heredity. They determine the traits of an organism because the proteins they code for carry out the work of the cell. Some proteins give cells structure, while others catalyze reactions or act as chemical messengers.

FIGURE 2: A gene is a section of DNA that codes for a certain protein.



Explain Imagine that a chromosome was compared to a novel. What could a gene be compared to?

Proteins are the connection between DNA and traits. Proteins carry out most of the tasks in the cell, and as a result, greatly influence the cell's structure and function. Whether they are catalyzing chemical reactions, transporting molecules, or helping fight infections, proteins are essential components of the cell system.

FIGURE 3: Proteins have many different functions.

Function	Examples
Storage	Albumin (a protein found in egg whites)
Transport	Globin (a protein found in red blood cells)
Maintaining Homeostasis	Hormones (chemical messengers) Antibodies (components of the immune system that help defend the body from bacteria and viruses)
Movement	Myosin (motor protein involved in muscle movement) Kinesin (a motor protein that transports materials inside cells)
Structure	Parts of the cytoskeleton and muscle fibers Keratin (a protein that makes up hair, nails, feathers, and horns)
Catalyzing Reactions	Enzymes such as catalase, maltase, and lactase



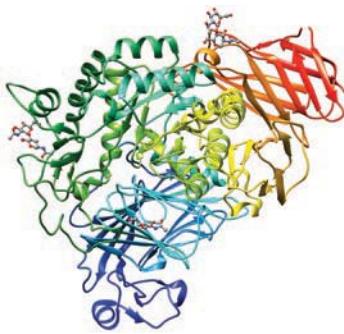
Gather Evidence Record evidence to explain why proteins are called the "workhorses" of the cell.



Structure and Function

Protein Modeling

FIGURE 4: This computer model can be used to study the enzyme maltase.



Each protein has a specific structure, which is coded for by a gene or set of genes. The image in Figure 4 is a computer model of a protein called maltase that catalyzes chemical reactions. As the name suggests, maltase breaks down the carbohydrate maltose into molecules of the simple sugar glucose.

A protein's structure helps it carry out a specialized function. The structure of maltase allows it to catalyze particular chemical reactions properly. If the structure of the protein is altered, it may not be able to carry out its function. Scientists are particularly interested in protein structure because proteins are involved in almost every cell process. Scientists use different types of technology to determine the structure of a protein to help them make a model using computer modeling software. This gives scientists a tool for experimenting with errors in protein structure to determine how these errors affect the protein's function. For example, scientists discovered that some human diseases result from a malfunctioning protein. Computer modeling technology has allowed research on proteins to advance greatly in recent years.



Explain What types of questions could a researcher investigate using a computer model of the enzyme maltase?

Stages of Protein Synthesis

The process of constructing proteins based on the DNA code has two main stages: transcription and translation. Transcription is the process of copying a sequence of DNA into an intermediate molecule called mRNA, or messenger RNA. mRNA is like a disposable copy of the DNA message. During translation, the mRNA message is converted into a polypeptide. One or more polypeptides make up a functional protein.

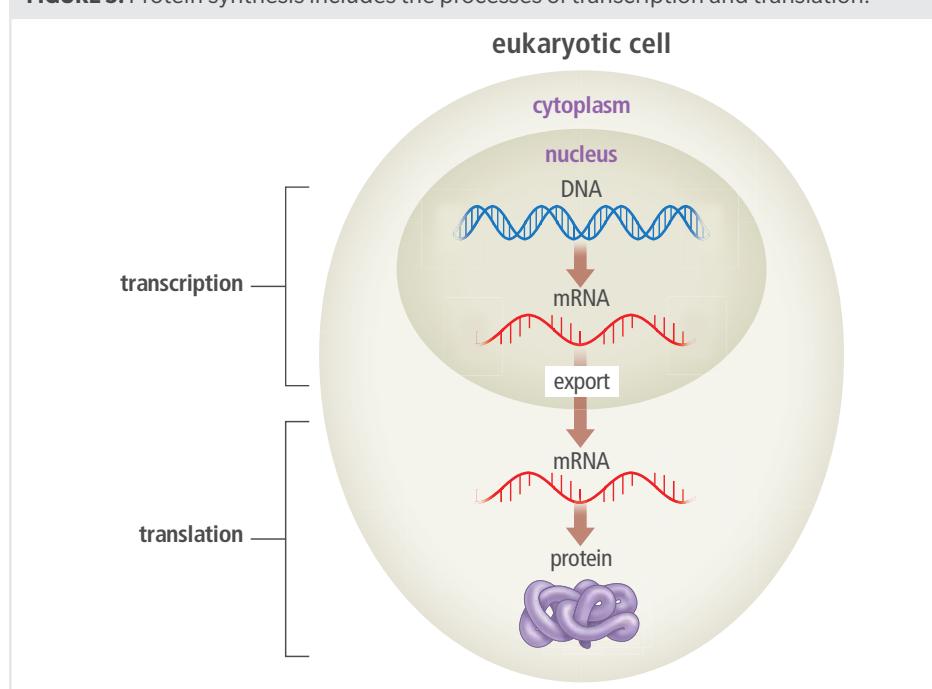


Predict Why do you think a “disposable copy” of the DNA code is necessary for protein synthesis?

Recall that a prokaryotic cell does not have a nucleus; instead, DNA “free-floats” within the cell. Thus, in these cells, transcription and translation all occur in the cytoplasm at approximately the same time. The translation of mRNA begins while the mRNA is still being transcribed.

In eukaryotic cells, however, DNA is located inside the nuclear membrane, so these processes are separated in both location and time. Transcription occurs in the nucleus of the cell, whereas translation occurs in the cytoplasm. The separation of transcription and translation in eukaryotic cells allows for additional processing of the mRNA before it is translated into a protein.

FIGURE 5: Protein synthesis includes the processes of transcription and translation.



Collaborate Imagine that the DNA code was compared to a recipe in a cookbook. What could RNA be compared to? Write your answer, and then compare it with a partner’s answer.



Analyze Identify the starting and ending materials for transcription and translation.

The RNA in eukaryotic cells goes through a processing step before it can be exported out of the nucleus. Before translation occurs, mRNA is “spliced” into a new combination of nucleotides. This extra modification of the mRNA code allows for the production of different proteins from a single gene. Thus, the mRNA transcript can be edited before it is translated.

Comparing DNA and RNA

RNA acts as a messenger, carrying information from DNA in the nucleus to protein synthesis in the cytoplasm. RNA is like a temporary copy of DNA that is used and then broken down. A molecule of RNA is similar to a molecule of DNA, but with some distinct differences. Figure 6 illustrates how the structures of these molecules compare. For example, DNA contains a sugar called deoxyribose, whereas RNA contains a sugar called ribose.

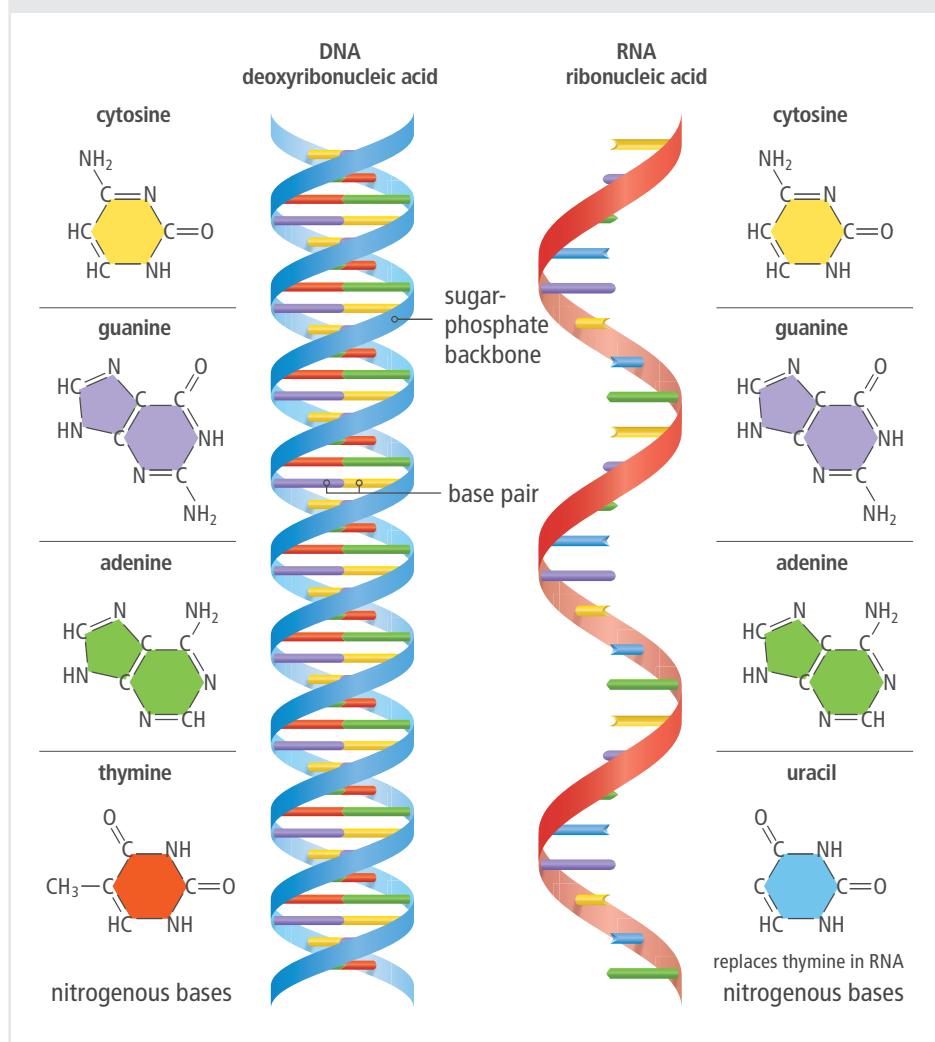


Language Arts Connection

Human

Immunodeficiency Virus, or HIV, is a retrovirus. Retroviruses contain RNA instead of DNA as genetic material. When HIV infects a cell, an enzyme called reverse transcriptase uses the RNA code to make a strand of DNA. This enzyme is not very precise, making lots of mistakes, allowing the virus to mutate rapidly. Using Internet resources, research HIV and reverse transcriptase. Prepare a report comparing protein synthesis in human cells to the process this retrovirus uses to transcribe its genetic material.

FIGURE 6: DNA and RNA have some similarities in their structures.



As you can see, RNA has one nitrogenous base, uracil, that differs from one of the bases found in DNA. This base is similar in structure to thymine, allowing it to form base pairs with adenine. RNA's unique single-stranded structure also allows some types of RNA to form complex three-dimensional shapes. As a result, some RNA molecules can catalyze reactions similar to the way in which protein enzymes do.



Explain Why is RNA necessary for protein synthesis?

Transcription

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In order to translate the DNA code into a protein, a temporary copy of the code is needed. This first stage of protein synthesis is called transcription. **Transcription** is the process of copying a sequence of DNA to produce a complementary strand of RNA. In eukaryotes, transcription occurs in the nucleus of the cell.



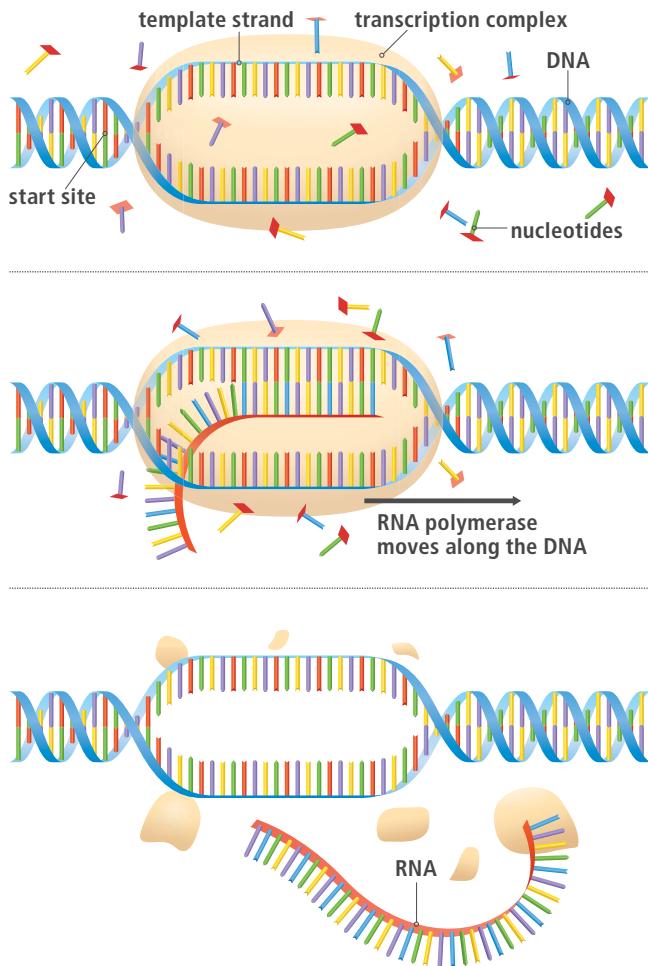
Predict Transcribe means to write. Why would we use the word transcribe to describe the process of making a complementary RNA sequence from a DNA template?

Steps of Transcription

During the process of transcription, a gene—not an entire chromosome—is transcribed into an RNA message. Transcription is catalyzed by RNA polymerases, enzymes that bond nucleotides together in a chain to make a new RNA molecule.

FIGURE 7: In transcription, enzymes use the DNA template to make a complementary strand of RNA.

[Explore Online](#)



1 In eukaryotic cells, a large transcription initiation complex consisting of RNA polymerase and other proteins assembles on the DNA strand and begins to unwind a segment of the DNA molecule. The complex assembles at a specific sequence of nucleotides along the DNA molecule called a promoter.

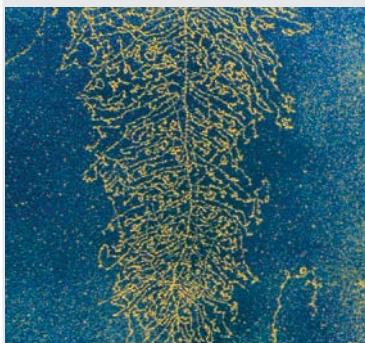
2 RNA polymerase, using one strand of DNA as a template, strings together a complementary strand of RNA nucleotides. RNA base pairing follows the same rules as DNA base pairing, except that uracil, not thymine, pairs with adenine. So, U pairs with A and G pairs with C. The growing RNA strand hangs freely as it is transcribed, and the DNA helix zips back together.

3 Transcription continues until an entire gene has been converted to RNA. The RNA strand detaches completely from the DNA.



Structure and Function Explain how the structure of the DNA molecule determines the structure of an RNA molecule during transcription.

FIGURE 8: These growing RNA strands are being transcribed from a single DNA strand.



Transcription can produce hundreds or thousands of copies of mRNA depending on the cell's needs. Transcription enables a cell to adjust to changing demands by making a single-stranded complement of only a segment of DNA, and only when that particular segment is needed. Many RNA molecules can be transcribed from a single gene at the same time to help produce more protein. Once RNA polymerase has transcribed one portion of a gene and has moved on, another RNA polymerase can attach itself to the beginning of the gene and start the transcription process again. This process can occur over and over again.



Analyze Why is the ability to produce multiple RNA transcripts at the same time useful in maintaining homeostasis in a cell?

Transcription produces three main types of RNA molecules, each with a unique function. Only one, mRNA, actually codes for proteins. Once mRNA is bound to ribosomal RNA (rRNA) in a ribosome, it is read by transfer RNA (tRNA) molecules that carry amino acids to bind to the developing protein.

FIGURE 9: Transcription produces three main types of RNA.

Type of RNA	mRNA	rRNA	tRNA
Model			
Function	An intermediate message that is translated to form a protein.	Forms subunits of ribosomes, which are the cell's protein factories.	Carries, or "transfers" amino acids to the ribosome to help make the growing protein.



Model Write a complementary mRNA sequence for the DNA sequence below. Remember that RNA contains uracil instead of thymine.

DNA sequence: TCA GGT ACG CTT

The next main stage of protein synthesis—translation—can begin once transcription is complete. However, the RNA strand must be processed before it can exit the nucleus in eukaryotes. This step occurs during, or just after, transcription. We will examine RNA processing in another lesson.



Explain Transcription and DNA replication are often compared to one another because they have many similarities. However, they do not have the same functions. Make a graphic organizer to compare and contrast DNA replication and transcription in terms of their functions, inputs, and final products.

Translation

In order to complete protein synthesis, the language of mRNA must be translated into the language of proteins. How does a language consisting of only four characters translate into a language of 20 amino acids? Just as letters are strung together in the English language to make words, nucleotides are strung together to code for amino acids.

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So far, you have learned that transcription uses DNA to produce a complementary strand of RNA. In eukaryotes, this stage of protein synthesis occurs in the nucleus. Once the RNA is processed and leaves the nucleus through pores, it enters the cytoplasm. This is where the process of **translation** decodes the mRNA to produce a **protein**. Translation occurs in the cytoplasm of both prokaryotic and eukaryotic cells.



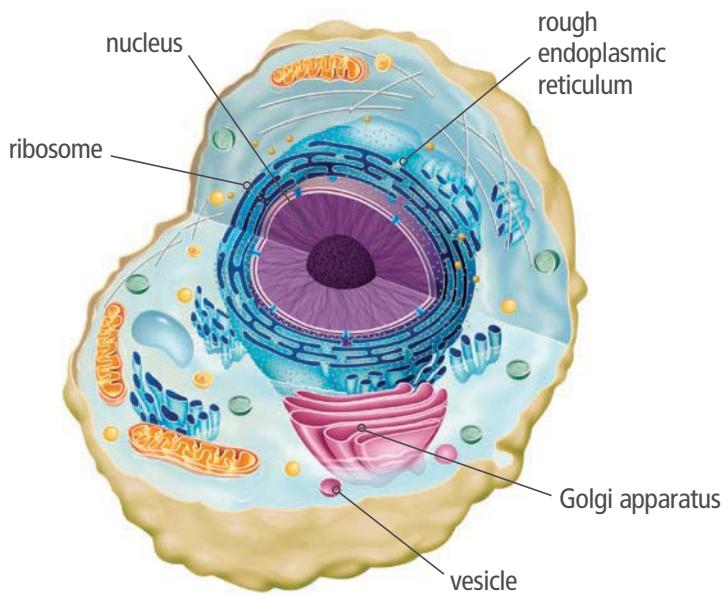
Collaborate In everyday language, translation means to express words in another language. Give an example of a message that would need to be translated.

mRNA
messenger RNA

Ribosomes

Once it is in the cytoplasm, the mRNA binds to organelles called **ribosomes**, which are made of rRNA and proteins. In plant and animal cells, ribosomes may be found floating free in the cytoplasm of the cell, or they may be attached to an organelle called the rough endoplasmic reticulum (rough ER). As proteins are being made, they enter the rough ER. Once inside, the proteins fold into their three-dimensional shapes, and some are modified by the addition of carbohydrate chains.

FIGURE 10: Animal Cell



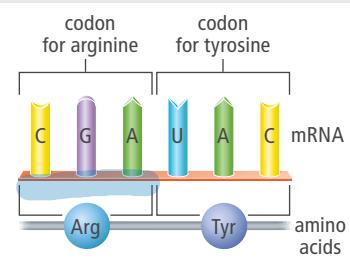
From the ER, proteins generally move to the Golgi apparatus to be processed, sorted, and delivered. Some packaged proteins are stored within the Golgi apparatus for later use. Others are transported to different organelles within the cell. Still others are carried to the membrane, where the vesicles carrying the proteins merge with the cell membrane, releasing the protein outside the cell through exocytosis.



Model Draw a flow chart to show the flow of RNA and proteins through the cell during protein synthesis.

Codons and Amino Acids

FIGURE 11: A codon is a sequence of three nucleotides that code for an amino acid.



Analyze There is one start codon, AUG, which identifies where translation will begin. Which amino acid corresponds to the start codon?

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Hands-On Activity



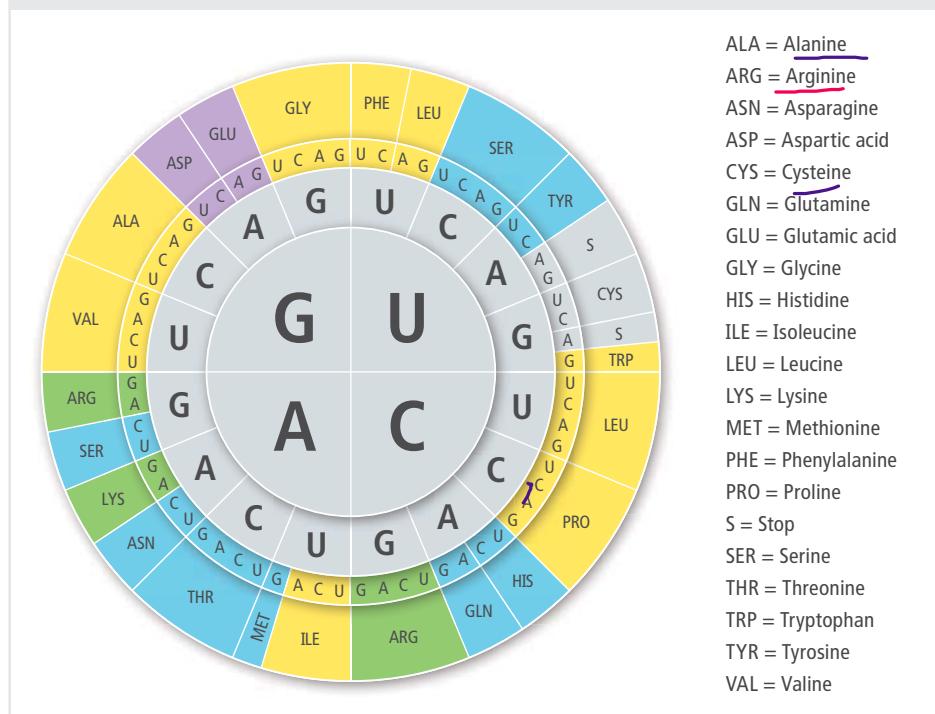
Modeling Protein Synthesis and Mutations Model transcription and translation by analyzing a DNA sequence and writing the corresponding mRNA codons and amino acid sequence. Then, build a model of the protein and fold it into its final shape. Finally, introduce a mutation and use your model to determine how the mutation affects the protein's structure.

The translation of RNA into protein is similar to what happens in a computer code. The information encoded in the nucleic acids of an mRNA molecule is “read” in groups of three nucleotides called codons. This is similar to the way a computer interprets the zeroes and ones of binary code strings into a program you can use. A codon is a three-nucleotide mRNA sequence that codes for an amino acid. Amino acids are the subunits, or monomers, that make up polypeptides. One or more polypeptides make up a protein.

Math Connection Suppose an mRNA molecule in the cytoplasm had 300 nucleotides. How many amino acids would be in the resulting polypeptide?

Scientists have determined what each combination of nucleotides in RNA code for in a protein and used this information to develop codon charts. A codon chart is used to identify which mRNA codons code for which amino acids. To read a circular codon chart, begin in the center and work outward. Start with the first letter of the codon, and pick the correct letter in the middle of the circle. Next, select the second letter of the codon, then follow to the third letter of the codon, and select the appropriate amino acid. Notice that many amino acids are coded for by more than one codon.

FIGURE 12: A codon chart shows which mRNA codons code for which amino acids.

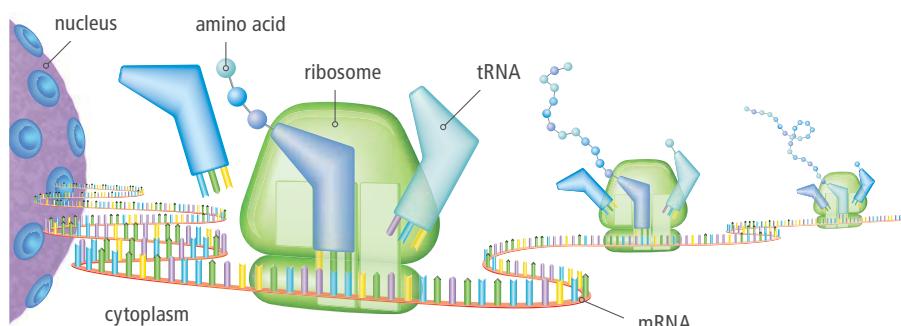


The genetic code is shared by almost all living organisms, as well as viruses. That means, for example, that the codon UUU codes for phenylalanine when that codon occurs in an armadillo, a cactus, a yeast, or a human. The common nature of the genetic code suggests that organisms arose from a common ancestor. It also means that scientists can insert a gene from one organism into another organism to make a functional protein. For these reasons, we say that the genetic code is nearly universal. There are, however, a few exceptions to the genetic code. For example, in one species of bacterium, UGA codes for tryptophan instead of functioning as a stop codon.

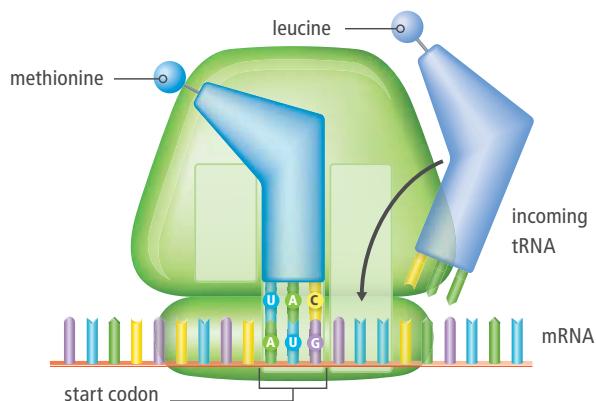
Steps of Translation

Explore Online 

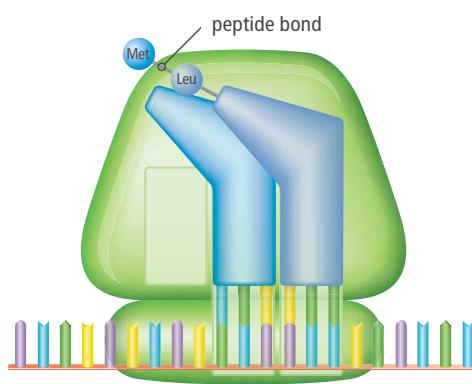
FIGURE 13: Translation converts an mRNA transcript into a polypeptide to build a protein.



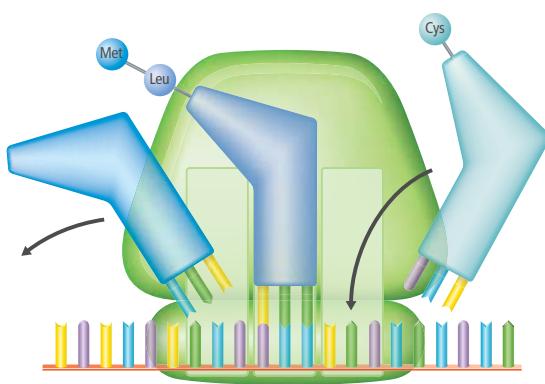
1 Before translation begins, a small ribosomal subunit binds to an mRNA strand in the cytoplasm. Then a tRNA with methionine attached binds to the AUG start codon. This binding signals a large ribosomal subunit to join. The ribosome pulls the mRNA strand through itself one codon at a time. The tRNA acts as a translator between mRNA and amino acids.



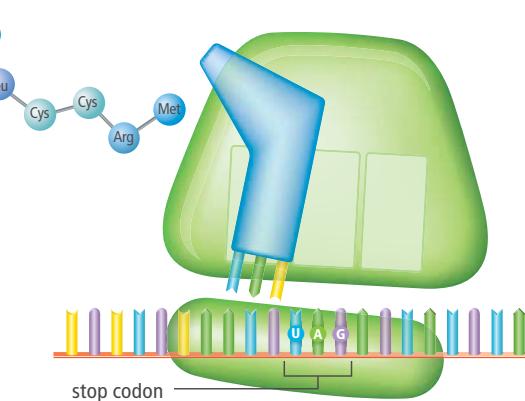
2 The exposed codon in the first site attracts a complementary tRNA molecule carrying an amino acid. The tRNA pairs with the mRNA codon, bringing it very close to the other tRNA molecule.



3 The ribosome helps form a peptide bond between the two amino acids and breaks the bond between the tRNA and its amino acid.



4 The ribosome pulls the mRNA strand along the length of one codon. The first tRNA is shifted into the exit site, where it leaves the ribosome and returns to the cytoplasm to pick up another amino acid. The first site is empty again, exposing the next mRNA codon.



5 The ribosome continues to translate the mRNA strand, attaching new amino acids to the growing protein, until it reaches a stop codon. Then the ribosome lets go of the new protein and breaks apart.



Explain An adapter can be thought of as a tool that converts an input to a new or modified use. Explain how the structure of the tRNA molecule helps it function as an adapter to translate the mRNA code into a sequence of amino acids.

Mutations and Proteins

Sometimes a **mutation** changes the sequence of nucleotides in an organism's **DNA**. Mutations that occur during replication can be classified as point mutations and frameshift mutations. In a point mutation, one nucleotide is replaced with a different nucleotide.



Structure and Function

FIGURE 14: Mutations alter nucleotide sequences.

Original DNA Sequence

TAC AGA GGC CGT

Mutated DNA Sequence

TAC AGT GAC CGT



Explain Determine the amino acid sequence that would be formed before and after two point mutations. Complete the following:

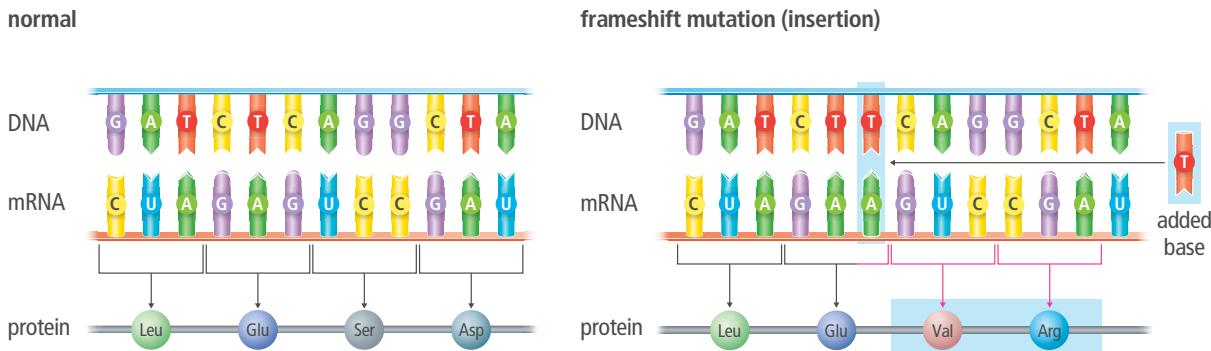
- Two DNA sequences are shown in Figure 14. Write the complementary mRNA sequence for each DNA sequence, and then use the codon chart to translate the mRNA code into a sequence of amino acids.
- Based on the amino acid sequences you wrote, does a point mutation always result in a change to the amino acid sequence? Support your answer with evidence.
- Suggest a specific scenario in which the DNA sequence could be mutated, but the structure and function of the resulting protein would not change.

Nucleotides must be correctly arranged for the protein to have the correct amino acid sequence. This order is called the reading frame. A change in the reading frame is called a frameshift mutation. A frameshift mutation involves the insertion or deletion of a nucleotide in the DNA sequence.

Analyze Could there be a frameshift mutation that would not affect the structure and function of the resulting protein? Explain your answer.

In an insertion mutation, an extra nucleotide is added into the DNA sequence. In a deletion mutation, a nucleotide is deleted from the DNA sequence. Because mRNA is read in groups of three nucleotides, the insertion or deletion of a nucleotide can affect the entire resulting amino acid sequence. For example, if an extra "a" is inserted into the sentence, "The cat ate the rat," the sentence becomes, "The caa tat eth era t."

FIGURE 15: Frameshift mutations change the reading frame, which results in changes in the sequence of amino acids.



Explain Summarize what you have learned so far to begin constructing an explanation for how the "language" of DNA is translated into the "language" of proteins. Construct a graphic organizer to compare the two phases of protein synthesis in terms of their function, where each process occurs in the cell, and final products.

Language Arts Connection

Making Synthetic Cells

What is the smallest number of genes an organism needs to survive? This is the question that a group of scientists in California set out to answer when they made the first synthetic cells. Led by biologist Craig Venter, the team wanted to build a full set of genes, or genome, and 'install' it in a new cell, much like installing new software on a computer.

At first, the group sequenced the genome of a bacterium called *Mycoplasma genitalium*. This tiny microbe has the smallest genome of any known free-living organism. Its DNA holds the instructions to make only 485 proteins. The scientists then inactivated genes one at a time to determine which genes were necessary for life. As a result of these tests, the researchers proposed that 375 genes were essential for life.

To test the hypothesis that an organism could survive with only these genes, Venter and his team started building a complete genome by linking together segments of DNA. The segments of DNA were produced chemically by adding one of the four nucleotides (A, T, G, and C) to a chain of DNA in a certain order. Enzymes then linked the segments together.

The group had built a complete genome. They also included watermarks in the non-protein-coding sections of the DNA. The watermarks used the genetic code to spell out words and phrases. The watermarks also signified that the genome was synthetic and not found in nature.

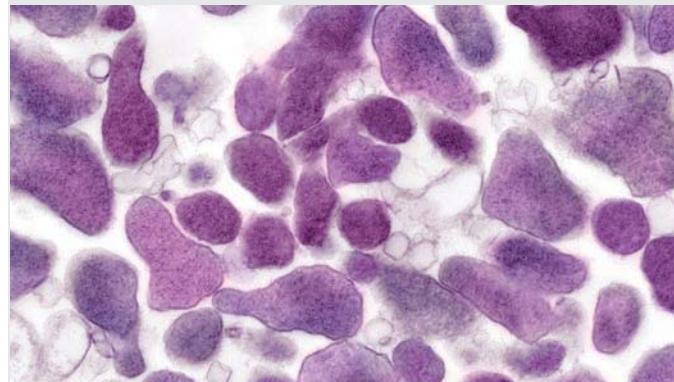
The slow growth rate of *M. genitalium* led the team to switch to a new species of bacteria called *Mycoplasma mycoides*. The scientists synthesized the new species' genome and implanted it into a different species of bacterium. They had reached their goal of making a synthetic cell. However, the genome was based on a copy of an existing genome, and it still contained more than 1 million DNA bases.

The team carried out further tests to determine the genes that were absolutely necessary for life. They mixed and matched different segments of DNA to see which combinations resulted in viable cells. This helped the researchers decide which genes to include in their design.

Venter and his group finally designed a synthetic cell called Syn3.0, which contained just 473 genes. Most of the genes with known functions were involved in expressing the DNA code. They were necessary for transcription, translation, protein folding, RNA modification, and RNA regulation. A smaller percentage were involved in DNA replication, cell division, and related functions. These genes allowed Syn3.0 to successfully replicate itself.

About a third of the genes had unknown functions. Some of these are found in other organisms like humans, and scientists hope to use Syn3.0 to study these genes and their functions. Synthetic cells could also be used to make products such as medicines and fuels. However, there are still many challenges to overcome and ethical issues to consider.

FIGURE 16: *Mycoplasma genitalium* has the smallest genome of all known free-living organisms.



Language Arts Connection Prepare for a discussion by searching for information about synthetic cells. What are some of the possibilities and concerns with using synthetic cells in research? Record evidence statements related to this question, and record the source for each statement. When you are ready, follow your teacher's guidelines for participating in the discussion. When you speak, give evidence to support your claims, and cite the sources of your evidence.



MODELING PROTEIN SYNTHESIS
AND MUTATIONS



EXPLORING PROTEIN
CRYSTALLIZATION

Go online to choose one of
these other paths.

Lesson Self-Check

CAN YOU EXPLAIN IT?

FIGURE 17: Computer programmers develop coded instructions that a computer uses to perform a task. Similarly, DNA is the genetic code that cells use for protein synthesis.



You have explored the cellular process that produces proteins from DNA code. In many ways it is similar to the way that humans translate our language into a language that computers can understand. The binary code that computers understand is made up of zeroes and ones, sometimes called machine code. However, computer programmers do not typically write programs directly in this binary code. Instead, they use programming languages, such as C++ or JavaScript, which act as translators between the programmer and the computer.



Explain Refer to the notes in your Evidence Notebook to answer the following questions to explain how the language of DNA is translated to the language of proteins and how this process compares to computer programming.

1. How does the four-letter DNA language encode instructions for making thousands of different proteins?
2. Which molecules act as the translators in the process of protein synthesis?
3. How is the process of protein synthesis similar to the process of programming a computer? How is it different?

CHECKPOINTS**Check Your Understanding**

- 1.** A student is planning to draw a model of DNA and a model of RNA. Which of the following should the student include in the DNA model and NOT the RNA model?
 - a. a double helix
 - b. the nucleotide uracil
 - c. the sugar ribose
 - d. a phosphate group

- 2.** Which of the following is evidence that would support the claim that DNA has been transcribed into RNA?
 - a. A temporary, complementary copy of the DNA has been produced.
 - b. An exact, permanent copy of the DNA has been produced.
 - c. A complementary, permanent copy of RNA has been produced and it replaces DNA.

- 3.** Which statement correctly compares the impact of frameshift mutations and point mutations on polypeptides?
 - a. Point mutations have a greater impact because they always change the resulting protein.
 - b. Frameshift mutations have a greater impact because they always substitute the first nucleotide in a codon.
 - c. Frameshift mutations have a greater impact because they shift the entire codon sequence following them.
 - d. Point mutations have a greater impact because they always cause a change in the amino acid sequence.

- 4.** Place these steps in order to describe the process of transcription.
 - a. RNA polymerase uses the DNA strand as a template to synthesize a complementary strand of RNA.
 - b. The RNA strand grows until an entire gene has been transcribed.
 - c. The complex of RNA polymerase and proteins breaks apart.
 - d. The DNA is unwound and a specific sequence of nucleotides is sequenced along the promoter.
 - e. A large complex consisting of RNA polymerase and other proteins assembles on the DNA strand.

- 5.** Draw a model showing how the three types of RNA interact to translate an mRNA code into a sequence of amino acids.

- 6.** Which flow chart best summarizes the process of protein synthesis?
 - a. rRNA → DNA → mRNA
 - b. Protein → mRNA → DNA
 - c. mRNA → DNA → protein
 - d. DNA → mRNA → protein

- 7.** Fill in the correct terms to complete this statement about eukaryotes. Some terms may be used more than once.

cytoplasm, amino acids, nucleus, ribosomes, mRNA, DNA, protein

DNA replication occurs in the _____ of the cell and produces two identical strands of _____. Protein synthesis is made up of two stages. Transcription occurs within the _____ and uses the DNA template to make a complimentary strand of _____. This molecule leaves the nucleus and enters the cell's _____ where _____ read along the strand of nucleotides. tRNA molecules bearing _____ enter the ribosome. The subunits are linked together to make a polypeptide, which is modified to make the final _____.

MAKE YOUR OWN STUDY GUIDE

In your Evidence Notebook, design a study guide that supports the main idea from this lesson:

Protein synthesis consists of two stages. In the first stage, the DNA code is transcribed to make an mRNA strand. The mRNA strand is then translated into a sequence of amino acids.

Remember to include the following information in your study guide:

- Use examples that model main ideas.
- Record explanations for the phenomena you investigated.
- Use evidence to support your explanations. Your support can include drawings, data, graphs, laboratory conclusions, and other evidence recorded throughout the lesson.

Consider how models of protein synthesis can be used to determine the inputs and outputs at each step, as well as where each step of the process occurs in the cell.

Gene Expression and Regulation

The human genome has 3 billion base pairs. The fruit fly genome has 165 million.

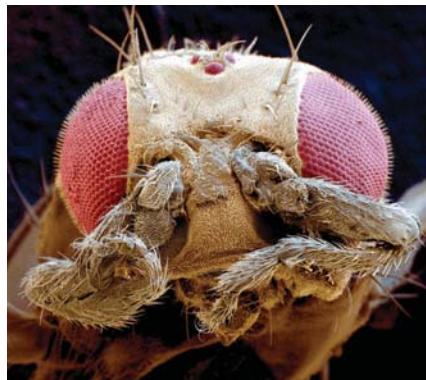
CAN YOU EXPLAIN IT?



Gather Evidence

As you explore the lesson, gather evidence for how gene expression is regulated in cells.

FIGURE 1: In the wild-type fruit fly (left), antennae developed normally. In the mutant fruit fly (right), a mutation caused legs to form in place of the antennae.



Most organisms share a group of genes called homeobox genes. One set of homeobox genes, called *Hox* genes, direct the formation of many body structures during the development of the embryo. Mutations in these genes can cause developmental disorders, including body parts growing in unexpected places, as shown in Figure 1.

We now know that *Hox* genes are shared by a wide array of animals, from fruit flies to jellyfish to humans. *Hox* genes define the head-to-tail pattern of development in animal embryos. This helps explain why so many animals look the same during the embryonic stage. *Hox* genes make segments in a larva or embryo that develop into specific organs and tissues.



Predict How might changes in genes be responsible for mutations, such as the mutation that causes legs to grow in place of antennae in a fruit fly?

Regulating Gene Expression

Most of the cells that make up your body have the same DNA. Red blood cells are one of the exceptions. Mature red blood cells do not contain DNA. However, the rest of your body cells, such as all the different cell types that make up each of your organs, have the same DNA. If they have the same DNA, how can these cells be so different from each other? The answer lies in the fact that some genes, and the proteins they encode, control the expression of other genes.

Gene Expression

Typically, a gene is considered “expressed” if transcription of mRNA occurs. However, the mRNA can undergo modification or be broken down before it is translated into a protein. **Gene expression** is the process by which the nucleotide sequence of a gene directs protein synthesis. In this way, cells use protein synthesis to respond to particular needs and react to changes in their environment.

FIGURE 2: Every gene has a locus, or specific position on a chromosome.

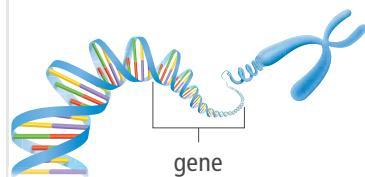
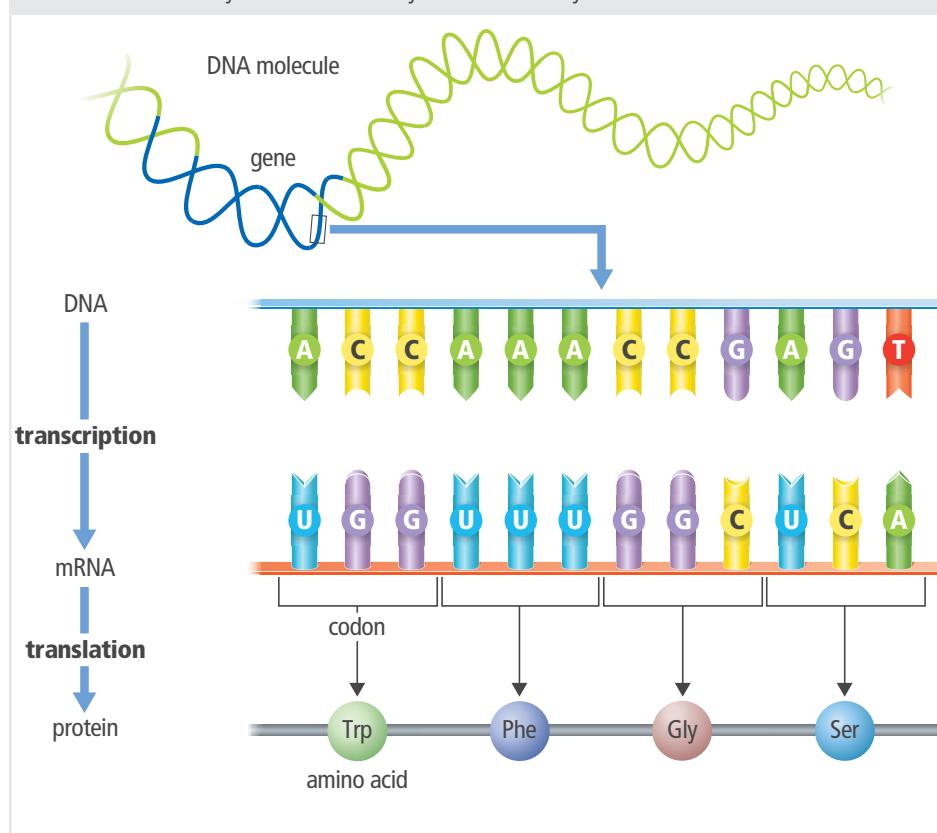


FIGURE 3: Protein Synthesis in Prokaryotes and Eukaryotes



Explain How are genes, proteins, and cell processes related?

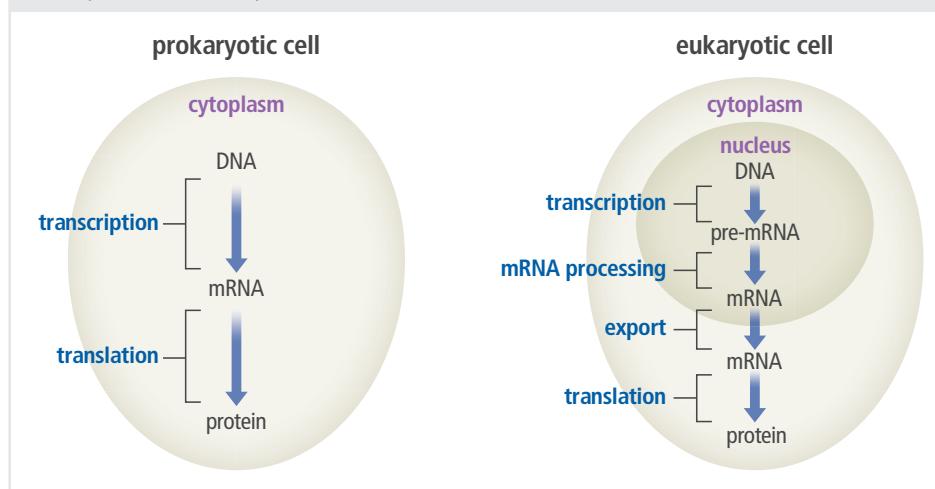


Collaborate With a partner, discuss these questions: What does the term “expression” mean in everyday language? How does the meaning of this word relate to the concept of gene expression?

According to the central dogma of molecular biology, information flows in one direction from DNA to RNA to proteins. This means there are multiple steps along the way where protein synthesis can be regulated, or controlled.

Both prokaryotic cells and eukaryotic cells regulate gene expression, though they do so differently. In eukaryotes, gene expression is regulated at many different steps. In contrast, the ability of prokaryotes to regulate gene expression is much simpler.

FIGURE 4: In prokaryotic cells, transcription and translation both occur in the cytoplasm at about the same time. In eukaryotic cells, where DNA is located inside the nucleus, these processes are separated both in location and time.



Structure and Function Use the model in Figure 4 to write an explanation for how differences in cell structure are related to the differences in the ways gene expression is regulated in prokaryotic and eukaryotic cells.

Gene Regulation in Prokaryotes

Because transcription and translation occur at the same time in prokaryotic cells, gene expression in these cells is mainly regulated at the start of transcription. Prokaryotic cells control gene expression using operons to turn genes "on" or "off" during transcription. An **operon** is a region of DNA that includes a promoter, an operator, and one or more structural genes that code for all the proteins needed to do a specific task. The **promoter** is a segment of DNA that helps the enzyme RNA polymerase locate the starting point for transcription.

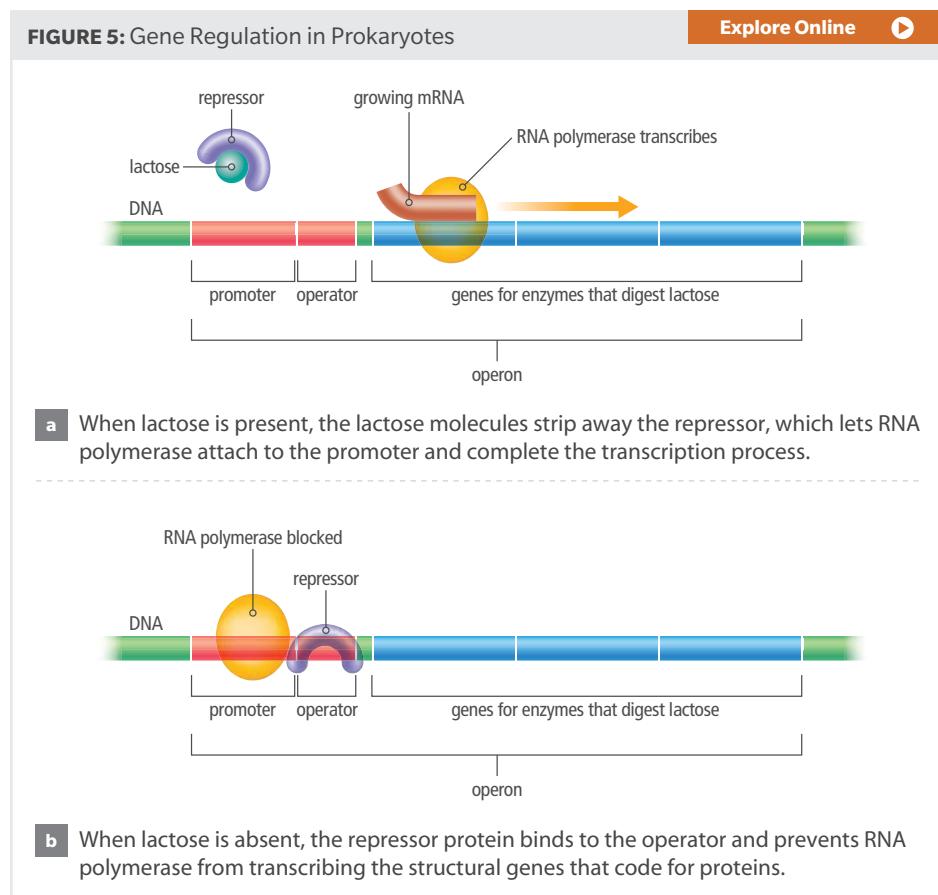
 **Analyze** What might be the benefit of turning genes on and off?

The DNA segment that actually turns genes on or off is the **operator**. It interacts with proteins that increase the rate of transcription or block transcription from occurring. Bacteria have much less DNA than do eukaryotes, and their genes tend to be organized into operons. The *lac* operon was one of the earliest examples of gene regulation discovered in bacteria. The *lac* operon has three genes, which all code for enzymes that play a role in breaking down the sugar lactose.



Gather Evidence As you read, record information to help you construct an explanation for how prokaryotes respond to changes in their environment by controlling gene expression.

The ability of a cell to switch certain genes on or off was first discovered in 1961 by French scientists François Jacob and Jacques Monod. This major advance in our understanding of how genes work began with a study of how genes control lactose metabolism in the bacterium *Escherichia coli*. Jacob and Monod observed that the genes responsible for lactose metabolism were expressed only in the presence of lactose. When lactose was not present, the genes were shut off. Their questioning of how this happened led to the discovery of the *lac* operon. Scientists now had a basis for understanding how specific genes can be turned on when needed and turned off when not needed.



The *lac* operon acts like a switch. When lactose is present, the *lac* operon is switched on to allow transcription. The lactose binds to the repressor, which makes the repressor change shape and fall off the *lac* operon. RNA polymerase is able to transcribe the DNA into RNA. This RNA is translated to form enzymes that work together to break down the lactose.

When lactose is absent, the *lac* operon is switched off to prevent transcription of the *lac* genes, thus saving the cell's resources. Bacteria have a protein that can bind specifically to the operator. When lactose is absent, the protein binds to the operator, which blocks RNA polymerase from transcribing the genes. Because the protein blocks—or represses—transcription, it is called a repressor protein.



Model Imagine a bacterium has a mutated gene which codes for a malformed repressor protein. Draw a flow chart to show how this mutation would affect the bacterium's ability to digest lactose.

Explore Online



Hands-On Activity

Modeling Prokaryotic Operons

Operons Build a model of the *lac* operon. Then use your model to show how gene expression is regulated in prokaryotes.



Language Arts Connection

Make an informational guide explaining how the *lac* operon helps prokaryotes respond to changes in their environment. In your guide, explain the functions of the gene, promoter, operator, repressor, and RNA polymerase.

Gene Regulation in Eukaryotes

Gene regulation is complex for a reason: the complexity ensures that the correct gene is expressed in the correct cell at the correct time. Cells rely on information encoded in their DNA to regulate protein synthesis. In eukaryotes, there is a mechanism that controls when a gene is expressed, one that controls the amount of protein made, and still another that controls when synthesis of that protein stops. A gene may also include other nucleotide sequences that act to control its expression. These sequences include promoters and operators, which control the start of transcription.

Controlling Gene Expression

Because DNA and ribosomes are located in the cytoplasm of prokaryotic cells, both transcription and translation occur at the same time. As a result, the regulation of gene expression in prokaryotes is limited to a few steps during transcription. However, the cellular and chromosomal organization in eukaryotes is much more complex. This makes it possible for eukaryotes to regulate gene expression at many different points during protein synthesis.

Pre-Transcriptional Regulation

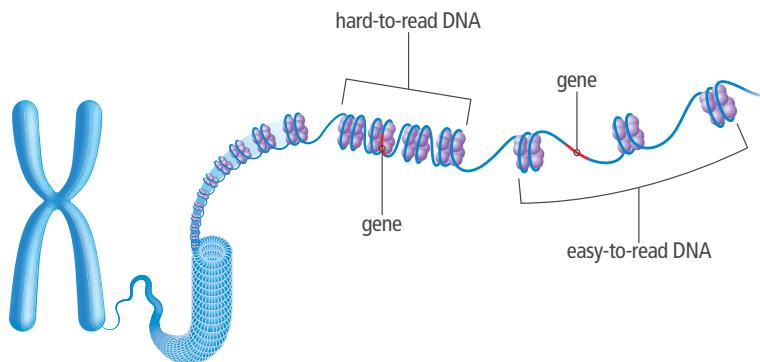
Language Arts Connection

Use Internet resources to research some of the recent discoveries in the field of epigenetics. Write a blog post to explain how a person's environment and their ancestors' environments can affect gene expression.

Recall that in eukaryotes, the DNA in chromosomes is bound tightly around proteins called histones. Chemical compounds are also added to the DNA to help regulate gene expression. All of these added chemical compounds are referred to collectively as the epigenome. The epigenome determines how easily the enzymes of transcription can access regions of the chromosome to turn genes on or off. When histones or DNA are changed chemically, the result may change the accessibility of the DNA for transcription.

Epigenetic changes can be caused by factors such as the age of the organism, inputs from the environment, and disease-causing organisms. Chemical changes to histones or DNA nucleotides may cause transcription of a DNA region either to begin or to stop. Epigenetic changes are heritable, even though they do not change the genome itself.

FIGURE 6: Epigenetic changes to chromosomes occur in a variety of ways. In one type of histone modification, the DNA molecule tightens, making it hard to read.



 **Predict** What would happen to a multicellular organism if every gene were expressed in every cell all the time?

 **Explain** How is gene expression related to how tightly DNA is wound around histones?

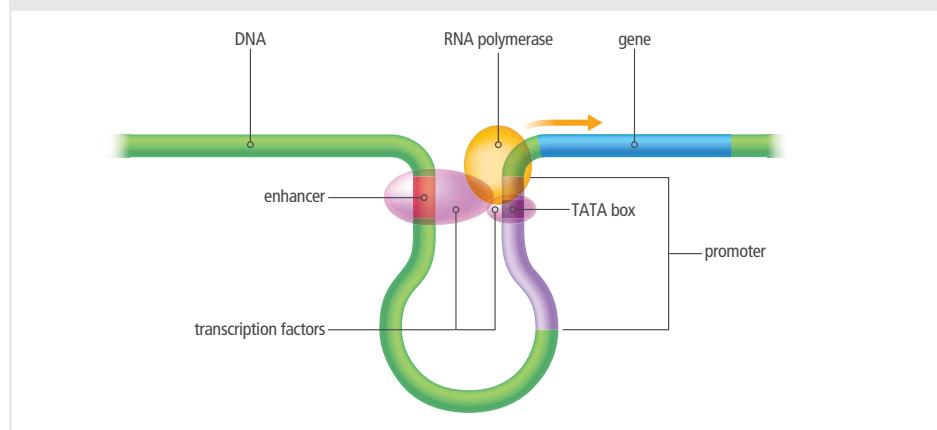
Transcriptional Regulation

Recall that a promoter is a segment of DNA that helps RNA polymerase recognize the start site of a gene. In eukaryotic cells each gene is controlled by a unique combination of promoters and other regulatory sequences. Most promoter sequences are unique to the gene, but some are repeated among many genes in many organisms. For example, most eukaryotic cells use a seven-nucleotide promoter with the sequence TATAAAA, called the TATA box.

Eukaryotic cells also have other types of promoters that are more specific to an individual gene. DNA sequences called enhancers speed up the transcription of a gene, while sequences called silencers act to slow down transcription. **Transcription factors** are proteins that bind to DNA sequences and control gene expression.

Transcription factors may bind to a promoter, an enhancer, or other sections of DNA near a gene. When the correct transcription factors are present, RNA polymerase recognizes the start site of the gene, and transcription begins.

FIGURE 7: In eukaryotes, transcription factors bind to promoters and other DNA sequences to help RNA polymerase recognize the start of a gene.



Explain Transcription factors occur in different combinations in different types of cells. How does this allow for variety in cell types?



Engineering

Using RNA Interference to Fight Disease

In the early 1990s, scientists working with the manipulation of color intensity in petunia plants saw something that was hard to explain. In an effort to increase the intensity of flower color, the scientists genetically modified petunia plants to overexpress the flower pigmentation gene for chalcone synthase (CHS). Some of the resulting flowers did indeed have the desired intense purple petals—but not all of them. Some flowers had purple and white petals, while others had completely white petals. Further investigation led to the discovery that both the introduced and naturally occurring forms of CHS had been turned off, or silenced, in some of these plants.

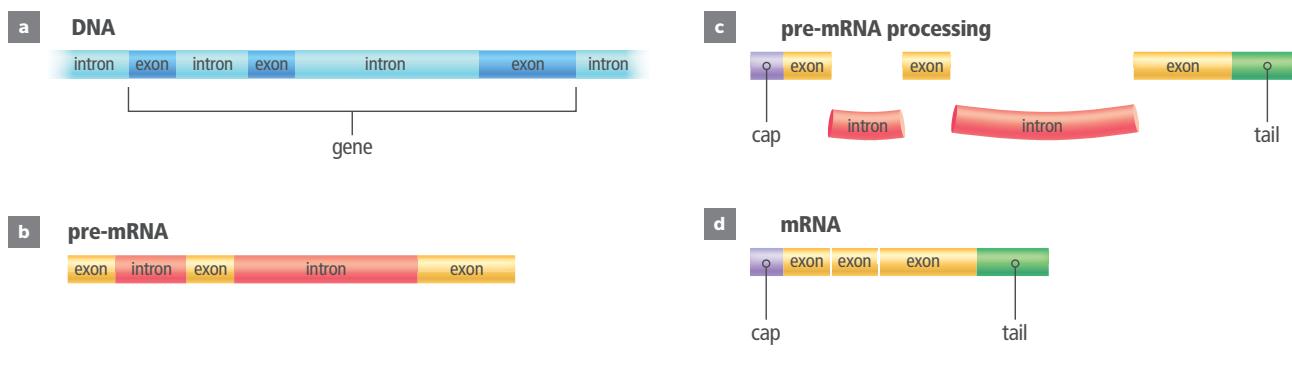
When the gene for the intense color was introduced to the plant, the cells used RNA interference (RNAi) to deactivate the gene. Small segments of double-stranded RNA began a series of reactions that degraded the mRNA molecules. RNAi does not normally occur in healthy cells, but cells may use it to fight off infections or the effects of tissue damage. The study of RNAi may lead to new treatments for a variety of diseases caused by harmful genes.

Analyze Huntington's disease is an inherited disorder that affects the nervous system, resulting in loss of coordination and declining brain function. This disease has been linked to a mutation in the HTT gene. Imagine you want to design an RNAi technology to silence this gene. Make a list of questions you would need to ask to define and delimit the problem.

Post-Transcriptional Regulation

The cell has a variety of mechanisms it can use at any stage after transcription to regulate gene expression. One method is mRNA processing, which edits the mRNA similar to the way a film editor cuts and splices the scenes of a movie.

FIGURE 8: An mRNA molecule typically undergoes processing during or immediately after DNA transcription.



The cell makes many changes to mRNA after transcription. A specialized nucleotide is added to the beginning of each mRNA molecule, forming a cap. This cap helps the mRNA strand bind to a ribosome and prevents the strand from being broken down too fast. The end of the mRNA molecule gets a string of nucleotides called the tail that improves stability and helps the mRNA molecule exit the nucleus. The “extra footage” in the mRNA molecule takes the form of nucleotide segments, called **introns**, that are not included in the final protein. The nucleotide segments that code for parts of the protein are called **exons**. Introns occur between exons. They are removed from an mRNA molecule before it leaves the nucleus. The cut ends of the exons are then joined together by a variety of molecular mechanisms.

Introns are an example of what is called noncoding DNA, which are regions of DNA that do not code for proteins. Scientists are still determining the role of noncoding regions of the human genome. It is thought that noncoding regions may play a role in regulating gene expression and in chromosome pairing and condensation.



Collaborate Why would you want to edit a rough cut of film? With a partner, discuss how this analogy relates to the transcription and translation of a gene.

Translational Regulation

Translation takes place after mRNA is moved into the cytoplasm, and it is the process that makes a protein from amino acids. In eukaryotes, gene expression may also be regulated by changes to the translation process. These changes depend mostly on the stability of the RNA molecule. For example, specific proteins help initiate the translation process. Changes in these proteins can prevent ribosomes from binding to mRNA, which slows or stops protein synthesis. These mechanisms allow eukaryotic cells to control protein production when conditions in the cell change rapidly.



Analyze Make a graphic organizer to summarize the mechanisms that allow eukaryotic cells to control gene expression at each stage of protein synthesis. How do these mechanisms compare to those in prokaryotes in terms of structure and function?

Factors That Influence Gene Expression

What determines whether a gene gets turned on or turned off? Factors both inside and outside cells can influence whether a gene is expressed. When an organism is developing, its cells take on different structures by expressing different sets of genes. Gene expression can also be responsible for changes that occur once the organism is grown. When the environment changes, some genes may need to be turned off, while others need to be expressed more frequently.



Gather Evidence

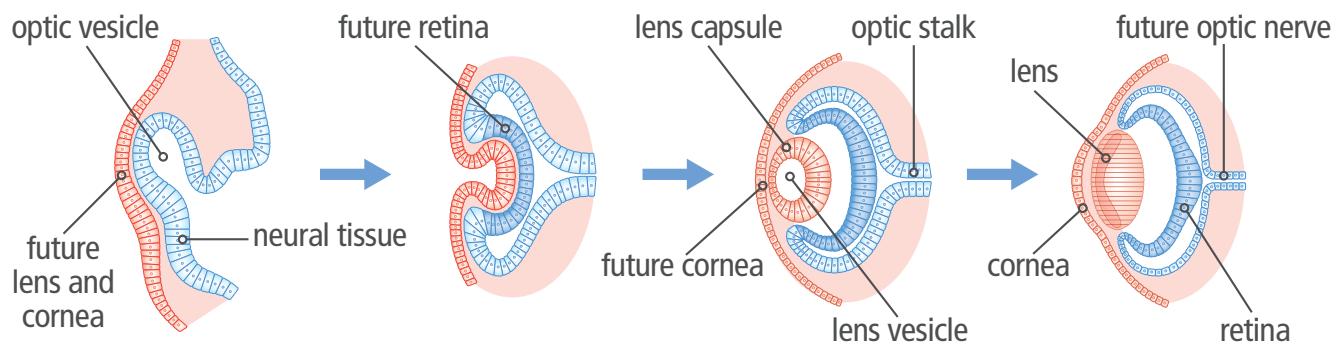
As you read, gather evidence to make a claim for how gene expression is related to cell differentiation.

Internal Factors

As an organism develops, its cells take on different structures by expressing different combinations of genes. Several internal factors regulate this process. One internal factor is the genetic makeup of the zygote. Many of the instructions for differentiation are included in the zygote's genome. These genes are expressed early in embryonic development and begin differentiation. Another factor that affects cell differentiation is the unequal distribution of molecules in the cytoplasm of the zygote during early stages of division. As cells divide, some cells have higher concentrations of certain molecules. These molecules regulate gene expression and help determine what type of cell each one becomes.

Cells in a developing embryo also influence the cells around them by sending and receiving diffusible molecules that act as signals. Signals also come from molecules embedded in the cell membrane. Some of these proteins turn genes on and off to direct the developmental path of a cell. Still other molecules are enzymes that regulate gene expression by rapidly breaking down proteins made by translation.

FIGURE 9: During embryonic development, cell differentiation and growth form tissues and organs such as the eye.



Structure and Function Make a claim for how the cells in an organism can take on different structures and functions even though they all have the same genetic material.

External Factors

Factors in an organism's external environment can also affect gene expression. For example, a transcription factor called hypoxia-inducible factor, or HIF, is produced when oxygen concentrations are low. This transcription factor mediates important developmental processes such as apoptosis and blood vessel development. In tissues experiencing low oxygen concentrations, or hypoxia, HIF allows for the transcription of genes related to blood vessel development.

Light and Temperature

Environmental factors such as light and temperature can affect gene expression. For example, an Arctic fox's fur color changes from white during the winter to gray-brown in the summer months to better match its surroundings. This change in fur color is due to differences in melatonin secretion. In the winter, when day length is shorter, melatonin is secreted, so the pigment melanin is not produced and the fox's fur color is white. In the summer season, when daylight hours are longer, melatonin secretion is repressed, melanin is produced, and the fox's fur is gray-brown in color.

 **Model** Draw a flow chart to illustrate how changes in the external environment lead to changes in gene expression that affect the Arctic fox's fur color.

FIGURE 10: The Arctic fox expresses different colors of fur depending on the season.



Environmental temperature can also influence gene expression. Trees and other plants have mechanisms to adapt to changes in temperature, most of which function through the control of gene expression. In extreme heat conditions, which can cause stress in plants, multiple genes interact to reduce the rate of photosynthesis and stop plant growth. By studying the relationship between gene expression and photosynthesis, geneticists can work to improve the stability of crop plants during extreme weather conditions.

Drugs and Chemicals

Pregnant women are strongly advised to avoid a variety of drugs and chemicals, including tobacco, alcohol, and many medications. These substances can disrupt the normal timing of gene expression in a developing fetus. For example, a drug called thalidomide was sometimes prescribed to treat morning sickness in the late 1950s and early 1960s. However, doctors discovered that it interfered with limb formation in the developing embryos. Children born to mothers who took this drug were often born with shortened and improperly formed limbs.

 **Analyze** Why is a developing fetus especially susceptible to chemicals that affect gene expression?

 **Explain** Researchers have found that cancerous tumor tissue is often hypoxic, or deficient in oxygen. As a result, HIF is currently being considered as a possible tool in the fight against cancer. Explain how HIF-related approaches could be used to suppress tumor growth, and how this is related to regulating gene expression.

Careers in Science

Geneticist

Genetically, humans and fruit flies are similar. They share many of the same genes and, in some cases, use them in the same way. How do we know this? Geneticists work on the cutting edge of science and technology as they study genes, their functions, and their effects. They study not only how genes are inherited but also the role of genes in health, disease, and overall life span.

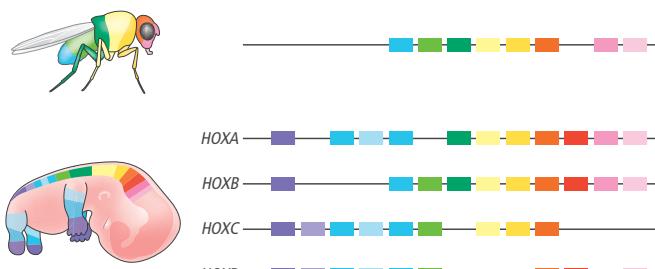
Geneticists use the fruit fly as a model organism for studying genetics. The short life span and small size of the fruit fly, as well as the ease with which they can be grown and maintained in a lab, make them model organisms to study. Most importantly, their entire genome is contained on just four chromosomes. This has allowed researchers to completely map the fruit fly genome.

Many known human disease genes have a recognizable match in the genetic code of the fruit fly. Using a systems approach to research, scientists, including molecular biologists, geneticists, and mathematicians, can use the information gained from studying fruit flies to provide insight into these diseases and many others. This same approach can be used to determine the mechanisms responsible for a number of different birth defects.

Studying fruit flies has led to many important discoveries. Observations of strange mutations in fruit flies, including legs where antennae should be or extra pairs of wings, led geneticists to the discovery of homeobox genes. Further investigation into these strange body modifications led to the finding that most of these changes were caused by mutations in a single set of homeobox genes, called *Hox* genes.

Vertebrates, such as humans, also have *Hox* genes. However, they are a bit more complex. In a fly, each segment of its body expresses only one *Hox* gene. Therefore, a mutation to a single *Hox* gene directly affects the corresponding body segment. In vertebrates, however, each segment has at least two, and up to four, *Hox* genes involved in its development.

FIGURE 11: The genes that determine a fruit fly's body plan are variations of the same genes that determine a human's, but they are expressed in different patterns.



Hox genes have a critical role in the regulation of cell differentiation. Some *Hox* genes also act as tumor suppressors, meaning they help control cell growth and prevent cells from growing or dividing too quickly.



Language Arts Connection

Make an informational career guide for a high school counselor to give to their students. In your guide, include text and media explaining what a job in genetics consists of and describing some of the topics geneticists are currently studying. Gather evidence from several different sources, including articles and scientific journals. Be sure to properly cite your sources in your informational guide. Use these questions to guide your research:

1. What are some of the topics that geneticists are currently studying?
2. What type of training and education is necessary to be a geneticist?
3. What is the importance of this career to society and to future generations?
4. If you were to become a geneticist, what questions would you like to answer through your work?

**TWINS: ARE THEY
EXACTLY THE SAME?**

"JUNK" DNA

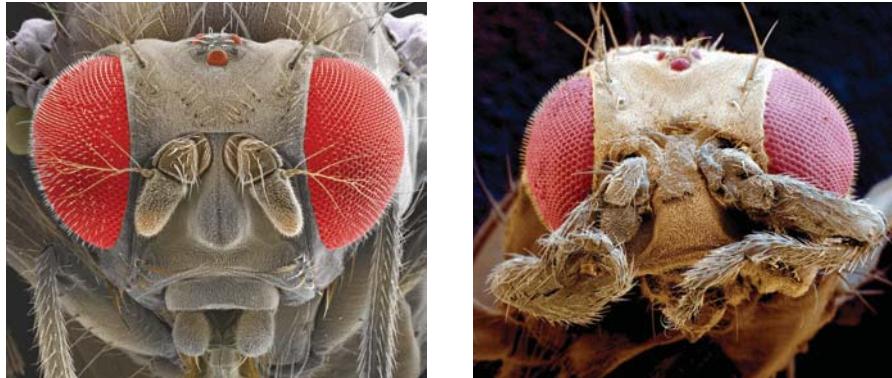
**GENES: LIFE
AFTER DEATH**

Go online to choose one of
these other paths.

Lesson Self-Check

CAN YOU EXPLAIN IT?

FIGURE 12: A normal wild-type fruit fly (left) and a mutant fruit fly (right).



Hox genes code for transcription factors that play an important role in the development of body structures. In the developing embryo, these transcription factors help initiate and regulate cell differentiation, cell adhesion, and cell migration. Controlling the order and timing of these events is critical for proper body development. As a result, these genes are very similar, or conserved, among many different species.

A mutation in a homeobox gene leads to the development of a body structure in the wrong position. For example, the effect of a mutation in the gene *Antennapedia* determines whether an insect body segment will grow antennae or legs. In the wild-type fruit fly, antennae develop normally. In the fly with a mutation in this gene, legs develop where the antennae should be. However, the rest of the fly develops normally. Although the misplaced legs look normal in structure, they do not work properly. Flies with these mutations usually do not live very long.



Explain Refer to the notes in your Evidence Notebook to explain why a mutation in *Hox* genes results in structural malformations such as the one shown in Figure 12. In your explanation, answer the following questions:

1. How do transcription factors regulate gene expression in eukaryotes? Create a model to illustrate the process, and write an explanation to accompany your model.
2. Why does a mutation in the *Antennapedia* gene affect body development in this way? How is this change in structure related to the regulation of gene expression?

CHECKPOINTS**Check Your Understanding**

- 1.** Which statement best explains why gene expression can be more complex and sophisticated in eukaryotic cells than in prokaryotic cells?
 - a.** Eukaryotic cells use a more complex genetic code.
 - b.** Eukaryotic cells use double-stranded DNA and single-stranded RNA.
 - c.** Transcription and translation are separated in time and space in eukaryotic cells.
 - d.** Gene expression in eukaryotic cells involves both transcription and translation.

 - 2.** Scientists have concluded that gene expression is responsible for the differentiation of the cells of a multicellular organism. Which two observations together most strongly support this conclusion?
 - a.** All cells produce the enzymes needed for energy metabolism.
 - b.** The DNA in all body cells of an organism is essentially identical.
 - c.** Gene expression can be regulated by a wide variety of mechanisms.
 - d.** Enzymes needed for digestion are produced only by cells lining the digestive tract.

 - 3.** Which of the following is an example of mRNA processing?
 - a.** non-coding segments of RNA are added to the beginning of an mRNA sequence
 - b.** double-stranded RNA initiates reactions that break apart RNA strands
 - c.** enzymes break down newly synthesized proteins
 - d.** RNA polymerase attaches to a promoter near a gene cluster

 - 4.** Draw a Venn diagram to compare gene expression in prokaryotes and eukaryotes.

 - 5.** The role of introns in newly transcribed mRNA has not yet been determined. How might introns help increase genetic diversity without increasing the size of the genome?
- 6.** Use these terms to complete the statement below:
- promoter, gene, transcription factors, RNA polymerase*
- A section of DNA which codes for a protein is called a _____. An enzyme called _____ reads along the DNA and produces mRNA in a process called transcription. Special proteins called _____ help this enzyme bind to a segment of DNA called the _____. When the correct factors are present in the nucleus, RNA polymerase can begin transcription.
- 7.** Which would be the best mechanism for maintaining homeostasis when conditions suddenly change in the cell? Pre-transcriptional, transcriptional, or translational regulation? Explain your reasoning.
- 8.** Which would most likely affect the structure and function of a protein, a mutation in an intron or a mutation in an exon? Explain your answer.

MAKE YOUR OWN STUDY GUIDE

In your Evidence Notebook, design a study guide that supports the main ideas from this lesson:

Gene expression is responsible for the differentiation of cells.

Gene expression is regulated differently in prokaryotic cells and eukaryotic cells.

Remember to include the following information in your study guide:

- Use examples that model main ideas.
- Record explanations for the phenomena you investigated.
- Use evidence to support your explanations. Your support can include drawings, data, graphs, laboratory conclusions, and other evidence recorded throughout the lesson.

Consider how the structure and function of DNA, RNA, and proteins make regulation of gene expression possible. Explain how alterations in these processes make mutations in organisms possible.

Computer Science Connection

DNA Data Storage The amount of digital data in the world is growing at a fast rate. People need room to store their personal data and institutions need room to store archives of information. Scientists have shown it is possible to code digital information into a strand of DNA and then recreate that information without errors. This technology is still being optimized, but there is real potential for DNA to be a solution for long-term data storage needs.



Using library and Internet resources, research DNA data storage. Create a multimedia sales pitch for a digital archive company explaining how DNA data storage works. Be sure to include information about how the structure and function of DNA makes it a safe way to store information. Think about what questions the client might ask, such as, "What barriers remain for this technology to overcome?"

FIGURE 1: DNA could be used to store digital data one day.



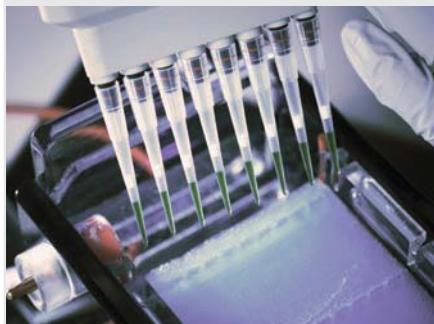
Social Studies Connection

Contributors to Scientific Knowledge The race to discover the structure of DNA involved many scientists with varied backgrounds. The experiences and expertise of the scientists allowed them to approach the problem from different angles. The determination of the double helix structure of DNA was a major accomplishment, but that wasn't the last discovery involving DNA. Since that time, there have been numerous advances in scientific knowledge related to the structure and function of DNA.



Using library and Internet resources, create a biosketch for a scientist that has contributed to our current understanding of DNA. A biosketch is a short, one or two-paragraph summary describing a person. Do not select a scientist whose contributions were outlined in the lesson. Be sure to use appropriate resources, cite evidence for how the scientist collaborated with others and contributed to scientific knowledge about DNA.

FIGURE 2: Many technologies, like gel electrophoresis, have enhanced our ability to manipulate and study DNA.



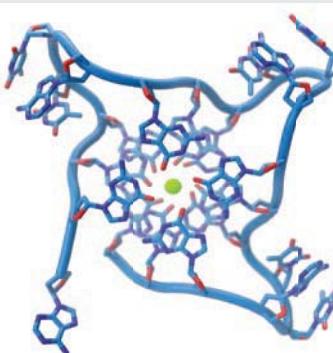
Life Science Connection

Four-Stranded DNA The double helix structure of DNA is very well-known, so it may be surprising to learn that DNA can take on other structures. One example is four-stranded DNA, which is common in cancer genes. The four-stranded molecule arises from a different folding structure that is linked to sequences of DNA that are rich in guanine.



Using library and Internet resources, research four-stranded DNA. How does the change in structure impact the function of the DNA molecule in gene regulation, especially cancer genes? Make a 3D model of both the double helix and the four-stranded structures of DNA. Then, deliver a presentation to the class that explains the differences in structure and function of these two types of DNA folding, including potential uses for the four-stranded molecule.

FIGURE 3: DNA can form a four-stranded structure.



SYNTHESIZE THE UNIT



In your Evidence Notebook, make a concept map, graphic organizer, or outline using the Study Guides you made for each lesson in this unit. Be sure to use evidence to support your claims.

When synthesizing individual information, remember to follow these general steps:

- Find the central idea of each piece of information.
- Think about the relationships between the central ideas.
- Combine the ideas to come up with a new understanding.

DRIVING QUESTIONS

Look back to the Driving Questions from the opening section of this unit. In your Evidence Notebook, review and revise your previous answers to those questions. Use the evidence you gathered and other observations you made throughout the unit to support your claims.

PRACTICE AND REVIEW

- 1. What is the primary function of DNA?**
 - a. store genetic information
 - b. translate genes into proteins
 - c. replicate genetic information for each cell
 - d. transcribe genetic information into RNA that can leave the nucleus

- 2. What evidence do codons provide for the common ancestry of all organisms?**
 - a. Almost all living things use codons to transcribe RNA to proteins.
 - b. Codons code for amino acids that are found in all living organisms.
 - c. Codons in almost all living organisms code for the same amino acid.
 - d. Codons are used to start and stop protein translation in almost all living things.

- 3. How does the epigenome assist in gene regulation?**
 - a. The epigenome controls which DNA sequences are accessible for transcription.
 - b. The epigenome regulates mRNA processing after transcription.
 - c. The epigenome controls the promoter sequence known as the TATA box.
 - d. The epigenome regulates translation in the cytoplasm.

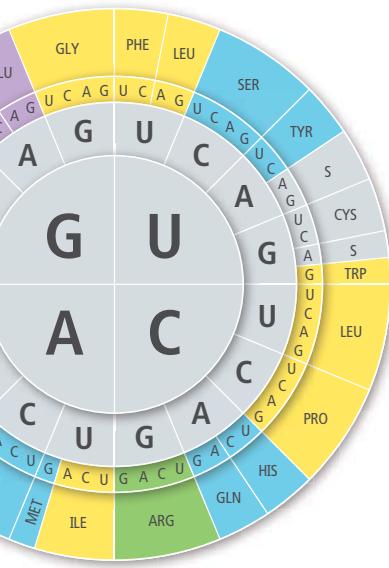
- 4. Which element provides instructions for cell differentiation?**
 - a. RNA
 - b. codons
 - c. genome
 - d. traits

- 5. Which characteristics describe both transcription and replication? Select all correct answers.**
 - a. unwinds the DNA double helix
 - b. controlled by complex enzymes
 - c. results in a full set of genetic information
 - d. occurs within the nucleus of eukaryotes.

- 6. What is the connection between a codon and an amino acid? Select all correct answers.**
 - a. A codon is a sequence of three nucleotides that specifies a particular amino acid.
 - b. A codon is made up of amino acids.
 - c. Each tRNA binds to a specific amino acid and has an anticodon that binds to a specific codon.
 - d. DNA is made up of codons and mRNA is made up of amino acids that attach to the DNA strand during translation.

Use the chart to answer questions 7–11.

FIGURE 4: The genetic code matches each mRNA codon with its amino acid or function.



ALA = Alanine	LYS = Lysine
ARG = Arginine	MET = Methionine
ASN = Asparagine	PHE = Phenylalanine
ASP = Aspartic acid	PRO = Proline
CYS = Cysteine	S = Stop
GLN = Glutamine	SER = Serine
GLU = Glutamic acid	THR = Threonine
GLY = Glycine	TRP = Tryptophan
HIS = Histidine	TYR = Tyrosine
ILE = Isoleucine	VAL = Valine
LEU = Leucine	

7. Which amino acid is represented by the codon CAG?
 - a. histidine
 - b. alanine
 - c. arginine
 - d. glutamine

8. What could happen if this DNA sequence CAG underwent a substitution point mutation? Select all correct answers.
 - a. The sequence could code for a stop codon.
 - b. The sequence could code for the same amino acid.
 - c. The sequence could code for a different amino acid.
 - d. The complete amino acid sequence for the protein could change.

9. What would happen if an adenine replaced the guanine in the DNA sequence GTC?
 - a. The glutamine would become lysine.
 - b. The glutamine would become valine.
 - c. The glutamine would remain the same.
 - d. The glutamine would become a stop codon.

10. Which amino acids would be most likely to be affected by a point mutation in the corresponding DNA sequence? Be specific and use evidence and reasoning to explain your answer.

11. Which DNA sequence would lead to the CAG codon in mRNA?

UNIT PROJECT

Return to your unit project. Prepare your materials into a final paper. Include an evaluation of your predictions, analysis, and conclusions.

Remember these tips while evaluating:

- Look at the empirical evidence—evidence based on observations and data. Does the evidence support your explanation regarding malformations in frogs?
- Consider if the explanation is logical. Does it contradict any evidence you have seen?
- Is there enough evidence from credible sources to support your conclusions?

Investigating Phenylketonuria

Phenylketonuria (PKU) is a recessive disorder that is characterized by high levels of phenylalanine in the blood. Phenylalanine is an amino acid that is normally broken down into components for the body to use. In people with PKU, the phenylalanine is not broken down and the amino acid accumulates in the blood. What causes the inability to break down phenylalanine in people suffering from PKU, and how does this change impact human health?

1. ASK A QUESTION

With your team, define a set of questions to be answered. Identify all the factors you will research to answer these questions. Outline the characteristics a complete answer should have.

2. CONDUCT RESEARCH

Investigate phenylketonuria. Use library and Internet resources to explore the cause and effect relationship between DNA structure, protein structure, and symptoms of the disease. As you do research, be sure to make notes about the sources of your evidence so you can correctly cite the sources and share them with others.

3. DEVELOP A MODEL

Use evidence from your research to develop a model of phenylketonuria. Include DNA, proteins, and symptoms in your model. You could draw a conceptual model or build a physical model out of common materials.

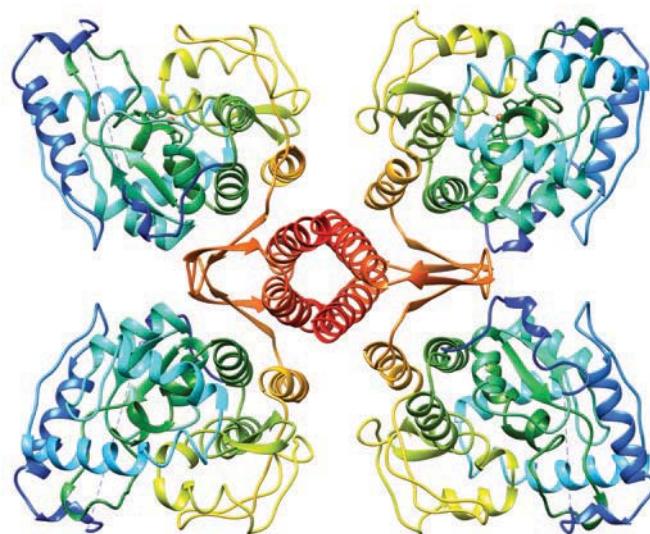
4. CONSTRUCT AN EXPLANATION

Use your answers to your questions to construct an explanation about the cause and effect relationship between DNA structure, protein structure, and symptoms of phenylketonuria.

5. COMMUNICATE

Present your findings as a poster that describes phenylketonuria, the enzyme involved, why it malfunctions, and possible avenues for addressing the issue. Your presentation should include images and data to support your claims.

FIGURE 5: A special enzyme is responsible for breaking down the amino acid phenylalanine.



CHECK YOUR WORK

A complete presentation should include the following information:

- guiding questions that are answered in the final presentation
- a model that shows the cause and effect relationship between DNA structure, protein structure, and phenylketonuria symptoms
- an explanation about how the structure of DNA determines the structure of the proteins involved and ultimately the traits associated with phenylketonuria