Chapter 8: From DNA to Proteins

**BIG IDEA** DNA and RNA are the genetic material in all living things and provide the molecular basis for reproduction and development.

### 8.1 Identifying DNA as the Genetic Material

#### TEKS 3F, 6A

### 8.2 Structure of DNA

#### TEKS 3F, 6A, 6B

**Data Analysis**

**INTERPRETING HISTOGRAMS**

#### TEKS 2G

### 8.3 DNA Replication

#### TEKS 3E, 5A, 9C

### 8.4 Transcription

#### TEKS 4B, 6C, 9C

### 8.5 Translation

#### TEKS 4B, 6C

### 8.6 Gene Expression and Regulation

#### TEKS 5C, 6C, 6D, 6E

### 8.7 Mutations

#### TEKS 6E

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- **QuickLab** Replication
- UV Light and Skin Cancer
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- Observing *Drosophila* Mutations
- Exploring Protein Crystallization

**Video Lab** DNA Extraction from Wheat Germ

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Unit 3: Genetics
Why is this mouse glowing?

This mouse’s eerie green glow comes from green fluorescent protein (GFP), which glows under ultraviolet light. Scientists put a GFP gene from a glowing jellyfish into a virus that was then used to infect a mouse egg. The jellyfish gene became part of the mouse’s genes. As a result, the mouse’s cells produce the same jellyfish protein and make the mouse glow. Researchers hope to use GFP to track cancer cells.

USING LANGUAGE
Finding Examples  When you are reading scientific explanations, finding examples can help you put a concept into practical terms. Thinking of your own examples will help you remember what you read.

YOUR TURN
For each category of items below, brainstorm as many examples as you can think of that could fit into the category.
1. hereditary traits
2. words that include the word part –her–
Identifying DNA as the Genetic Material

KEY CONCEPT  DNA was identified as the genetic material through a series of experiments.

MAIN IDEAS
- Griffith finds a “transforming principle.”
- Avery identifies DNA as the transforming principle.
- Hershey and Chase confirm that DNA is the genetic material.

Connect to Your World

Some people think that a complicated answer is better than a simple one. In the early 1900’s, for example, most scientists thought that DNA’s chemical composition was too repetitive for it to be the genetic material. Proteins, which are more variable in structure, appeared to be a better candidate. Starting in the 1920s, experiments provided data that did not support this idea. By the 1950s, sufficient evidence showed that DNA—the same molecule that codes for GFP in the glowing mouse—carries genetic information.

Griffith finds a “transforming principle.”

In 1928 the British microbiologist Frederick Griffith was investigating two forms of the bacterium that causes pneumonia. One form is surrounded by a coating made of carbohydrates. This form is called the S form because its colonies look smooth. The second form of bacteria does not have a smooth coating and is called the R, or rough, form. As you can see in Figure 1.1, when Griffith injected the two types of bacteria into mice, only the S type killed the mice. When the S bacteria were killed with heat before injection, the mice were unaffected. Therefore, only live S bacteria would cause the mice to die.

FIGURE 1.1 Griffith’s Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Griffith’s mice</td>
<td>A transferable material changed harmless bacteria into disease-causing bacteria.</td>
</tr>
</tbody>
</table>
Griffith next injected mice with a combination of heat-killed S bacteria and live R bacteria. To his surprise, the mice died. Even more surprising, he found live S bacteria in blood samples from the dead mice. Griffith concluded that some material must have been transferred from the heat-killed S bacteria to the live R bacteria. Whatever that material was, it contained information that changed harmless R bacteria into disease-causing S bacteria. Griffith called this mystery material the “transforming principle.”

**Infer** What evidence suggested that there was a transforming principle?

**MAIN IDEA**

Avery identifies DNA as the transforming principle.

What exactly is the transforming principle that Griffith discovered? That question puzzled Oswald Avery and his fellow biologists. They worked for more than ten years to find the answer. Avery’s team began by combining living R bacteria with an extract made from S bacteria. This procedure allowed them to directly observe the transformation of R bacteria into S bacteria in a petri dish.

Avery’s group next developed a process to purify their extract. They then performed a series of tests to find out if the transforming principle was DNA or protein.

- **Qualitative tests** Standard chemical tests showed that no protein was present. In contrast, tests revealed that DNA was present.
- **Chemical analysis** As you can see in **FIGURE 1.2**, the proportions of elements in the extract closely matched those found in DNA. Proteins contain almost no phosphorus.
- **Enzyme tests** When the team added to the extract enzymes known to break down proteins, the extract still transformed the R bacteria to the S form. Also, transformation occurred when researchers added an enzyme that breaks down RNA (another nucleic acid). Transformation failed to occur only when they added an enzyme that specifically destroys DNA.

In 1944 Avery and his group presented this and other evidence to support their conclusion that DNA must be the transforming principle, or genetic material. The results created great interest. However, some scientists questioned 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.

**Summarize** List the key steps in the process that Avery’s team used to identify the transforming principle.

**FIGURE 1.2 Avery’s Discoveries**

<table>
<thead>
<tr>
<th>CHEMICAL ANALYSIS OF TRANSFORMING PRINCIPLE</th>
<th>% Nitrogen (N)</th>
<th>% Phosphorus (P)</th>
<th>Ratio of N to P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>14.21</td>
<td>8.57</td>
<td>1.66</td>
</tr>
<tr>
<td>Sample B</td>
<td>15.93</td>
<td>9.09</td>
<td>1.75</td>
</tr>
<tr>
<td>Sample C</td>
<td>15.36</td>
<td>9.04</td>
<td>1.69</td>
</tr>
<tr>
<td>Sample D</td>
<td>13.40</td>
<td>8.45</td>
<td>1.58</td>
</tr>
<tr>
<td>Known value for DNA</td>
<td>15.32</td>
<td>9.05</td>
<td>1.69</td>
</tr>
</tbody>
</table>


**Analyze** How do the data support the hypothesis that DNA, not protein, is the transforming principle? **TEKS 3F**

**CONNECT TO**

**MICROBIOLOGY**

Much of our knowledge of the chemical basis of genetics has come from the study of bacteria. You will learn much more about bacteria in the chapter *Viruses and Prokaryotes*. **HMDScience.com**

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DNA as Genetic Material

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Conclusive evidence for DNA as the genetic material came in 1952 from two American biologists, Alfred Hershey and Martha Chase. Hershey and Chase were studying viruses that infect bacteria. This type of virus, called a bacteriophage (bak-TIR-ee-uh-fayj), or “phage” for short, takes over a bacterium’s genetic machinery and directs it to make more viruses.

Phages such as the ones Hershey and Chase studied are relatively simple—little more than a DNA molecule surrounded by a protein coat. This two-part structure of phages offered a perfect opportunity to answer the question, Is the genetic material made of DNA or protein? By discovering which part of a phage (DNA or protein) actually entered a bacterium, as shown in FIGURE 1.3, they could answer this question once and for all.

Hershey and Chase thought up a clever procedure that made use of 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.

- **Experiment 1** 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.

- **Experiment 2** Next, Hershey and Chase repeated the procedure with phages that had DNA tagged with radioactive phosphorus. This time, radioactivity was clearly present inside the bacteria.

From their results, Hershey and Chase concluded that the phages’ DNA had entered the bacteria, but the protein had not. Their findings finally convinced scientists that the genetic material is DNA and not protein.

**Apply** How did Hershey and Chase build upon Avery’s chemical analysis results? **TEKS 3F**

**FIGURE 1.3** This micrograph shows the protein coat of a bacteriophage (orange) after it has injected its DNA into an E. coli bacterium (blue). (colored TEM; magnification 115,000×)

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**8.1 Formative Assessment**

**REVIEWING MAIN IDEAS**

1. What was “transformed” in Griffith’s experiment? **TEKS 6A**
2. How did Avery and his team identify the transforming principle? **TEKS 3F**
3. Summarize how Hershey and Chase confirmed that DNA is the genetic material. **TEKS 3F**

**CRITICAL THINKING**

4. **Summarize** Why was the bacteriophage an excellent choice for research to determine whether genes are made of DNA or proteins?
5. **Analyze** Choose one experiment from this section and explain how the results support the conclusion.

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**CONNECT TO MENDELIAN GENETICS**

6. Describe how Mendel’s studies relate to the experiments discussed in this section. **TEKS 3F**
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Crack the Code

Build a Protein
Build a protein from a DNA code using enzymes, nucleotides, ribosomes, and tRNA.

Gene Regulation
Explore how genes regulate the digestion of milk sugar.

Animated Biology

Web Quest
Transgenic Organisms
Learn more about transgenic organisms. Then explore the potential benefits and risks of producing proteins with genes from other organisms.
8.2 Structure of DNA

**KEY CONCEPT** DNA structure is the same in all organisms.

**MAIN IDEAS**
- DNA is composed of four types of nucleotides.
- Watson and Crick developed an accurate model of DNA’s three-dimensional structure.
- Nucleotides always pair in the same way.

**Connect to Your World**

The experiments of Hershey and Chase confirmed that DNA carries the genetic information, but they left other big questions unanswered: What exactly is this genetic information? How does DNA store this information? Scientists in the early 1950s still had a limited knowledge of the structure of DNA, but that was about to change dramatically.

**MAIN IDEA**

**TEKS 3F, 6A, 6B**

DNA is composed of four types of nucleotides.

Since the 1920s, scientists have known that the DNA molecule is a very long polymer, or chain of repeating units. The small units, or monomers, that make up DNA are called nucleotides (NOO-klee-uh-TYDZ). Each nucleotide has three parts.

- A phosphate group (one phosphorus with four oxygens)
- A ring-shaped sugar called deoxyribose
- A nitrogen-containing base (a single or double ring built around nitrogen and carbon atoms)

One molecule of human DNA contains billions of nucleotides, but there are only four types of nucleotides in DNA. These nucleotides differ only in their nitrogen-containing bases.

The four bases in DNA are shown in **FIGURE 2.1**. Notice that the bases cytosine (C) and thymine (T) have a single-ring structure. Adenine (A) and guanine (G) have a larger, double-ring structure. The letter abbreviations refer both to the bases and to the nucleotides that contain the bases.

For a long time, scientists hypothesized that DNA was made up of equal amounts of the four nucleotides, and so the DNA in all organisms was exactly the same. That hypothesis was a key reason that it was so hard to convince scientists that DNA was the genetic material. They reasoned that identical molecules could not carry different instructions across all organisms.
**FIGURE 2.1 The Four Nitrogen-Containing Bases of DNA**

<table>
<thead>
<tr>
<th>PYRIMIDINES = SINGLE RING</th>
<th>PURINES = DOUBLE RING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Base</td>
<td>Structural Formula</td>
</tr>
<tr>
<td>thymine</td>
<td><img src="image1" alt="Thymine Structural Formula" /></td>
</tr>
<tr>
<td>cytosine</td>
<td><img src="image5" alt="Cytosine Structural Formula" /></td>
</tr>
</tbody>
</table>

**Compare** Which base is most similar in structure to thymine? **TEKS 6A**

By 1950 Erwin Chargaff changed the thinking about DNA by analyzing the DNA of several organisms. Chargaff found that the same four bases are found in the DNA of all organisms, but the proportion of the four bases differs somewhat from organism to organism. In the DNA of each organism, the amount of adenine approximately equals the amount of thymine. Similarly, the amount of cytosine roughly equals the amount of guanine. These A = T and C = G relationships became known as Chargaff’s rules.

**Summarize** How do the four DNA nucleotides differ in structure? **TEKS 6A**

**MAIN IDEA** **TEKS 3F, 6A**

**Watson and Crick developed an accurate model of DNA’s three-dimensional structure.**

The breakthrough in understanding the structure of DNA came in the early 1950s through the teamwork of American geneticist James Watson and British physicist Francis Crick. Watson and Crick were supposed to be studying the structure of proteins. Both men, however, were more fascinated by the challenge of figuring out DNA’s structure. Their interest was sparked not only by the findings of Hershey, Chase, and Chargaff but also by the work of the biochemist Linus Pauling. Pauling had found that the structure of some proteins was a helix, or spiral. Watson and Crick hypothesized that DNA might also be a helix.

**X-Ray Evidence**

At the same time, Rosalind Franklin, shown in **FIGURE 2.2**, and Maurice Wilkins were studying DNA using a technique called x-ray crystallography. When DNA is bombarded with x-rays, the atoms in DNA 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. Franklin’s data gave Watson and Crick the clues they needed. The patterns and angle of the X suggested that DNA is a helix consisting of two strands that are a regular, consistent width apart.
Back in their own laboratory, Watson and Crick made models of metal and wood to figure out the structure of DNA. Their models placed the sugar-phosphate backbones on the outside and the 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 produced a helix that varied in width. 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 a paper in the journal *Nature*. **FIGURE 2.3** shows their double helix (DUB-uhl HEE-likes) model, in which two strands of DNA wind around each other like a twisted ladder. The strands are complementary—they fit together and are the opposite of each other. That is, if one strand is ACACAC, the other strand is TGTGTG. The pairing of bases in their model finally explained Chargaff’s rules.

**Apply** How did the Watson and Crick model explain Chargaff’s rules?

**Nucleotides always pair in the same way.**

The DNA nucleotides of a single strand are 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, sort of like a twisted ladder. 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.

As shown in **FIGURE 2.4**, the bases of the two DNA strands always pair up in the same way. This is summarized in the base pairing rules: 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 and the ability of the
1. How many types of nucleotides are in DNA, and how do they differ? **TEKS 6A**
2. How are the base pairing rules related to Chargaff’s research on DNA? **TEKS 3F**
3. Explain how the double helix model of DNA built on the research of Rosalind Franklin. **TEKS 3F**

### Critical Thinking

4. **Infer** Which part of a DNA molecule carries the genetic instructions that are unique for each individual: the sugar-phosphate backbone or the nitrogen-containing bases? Explain. **TEKS 6A**
5. **Predict** In a sample of yeast DNA, 31.5% of the bases are adenine (A). Predict the approximate percentages of C, G, and T. Explain.

### Formative Assessment

**Self-Check**

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**CorrectionKey = A**

**Formative Assessment**

**8.2**

**Reviewing**

**Main Ideas**

**CONNECT TO**

**Evolution**

6. The DNA of all organisms contains the same four bases (adenine, thymine, cytosine, and guanine). What might this similarity indicate about the origins of life on Earth? **TEKS 6B, 7A**
Interpreting Histograms

A histogram is a graph that shows the frequency distribution of a data set. First, a scientist collects data. Then, she groups the data values into equal intervals. The number of data values in each interval is the frequency of the interval. The intervals are shown along the x-axis of the histogram, and the frequencies are shown on the y-axis.

Model
The histogram at right shows the frequency distribution of the ages of winners of the Nobel Prize in Medicine at the time of winning. Francis Crick was 46 and James Watson was 34 when they were jointly awarded a Nobel Prize in Medicine in 1962.

According to the histogram, the most winners have been between 50 and 59 years old at the time of winning. Only five scientists have been between the ages of 80 and 89 at the time of winning a Nobel Prize in Medicine.

Practice Interpret a Histogram
The histogram to the right categorizes data collected based on the number of genes in 11 species.

1. Identify How many species had between 10,001 and 15,000 genes?
2. Analyze Are the data in graph 2 sufficient to reveal a trend in the number of genes per species? Explain your reasoning.
DNA Replication

**KEY CONCEPT** DNA replication copies the genetic information of a cell.

**MAIN IDEAS**
- Replication copies the genetic information.
- Proteins carry out the process of replication.
- Replication is fast and accurate.

**CONNECT TO YOUR WORLD**
Do you know that some of your cells are dying right now? You may live to be 100 years old, but most of your cells will have been replaced thousands of times before you blow out the candles on that birthday cake. Every time that cells divide to produce new cells, DNA must first be copied in a remarkable process of unzipping and zipping by enzymes and other proteins. The next few pages will take you through that process.

**MAIN IDEA** Replication copies the genetic information.

One of the powerful features of the Watson and Crick model was that it suggested a way that DNA could be copied. In fact, Watson and Crick ended the journal article announcing their discovery with this sentence: “It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material.”

Recall that the bases that connect the strands of DNA will pair only in one way, according to the rules of base pairing. An A must bind with a T, and a C must bind with a G. If the base sequence of one strand of the DNA double helix is known, the sequence of the other strand is also known. Watson and Crick realized that a single DNA strand can serve as a template, or pattern, for a new strand. This process by which DNA is copied during the cell cycle is called replication.

Suppose all of your classmates took off their shoes, placed their left shoe in a line, and tossed their right shoe into a pile. You could easily pick out the right shoes from the pile and place them with the matching left shoes. The order of the shoes would be preserved. Similarly, a new strand of DNA can be synthesized when the other strand is a template to guide the process. Every time, the order of the bases is preserved, and DNA can be accurately replicated over and over again.

Replication assures that every cell has a complete set of identical genetic information. Recall that your DNA is divided into 46 chromosomes that are replicated during the S phase of the cell cycle. So your DNA is copied once in each round of the cell cycle. As a result, every cell has a complete set of DNA.
The fact that cells throughout the body have complete sets of DNA is very useful for forensic scientists. They can identify someone from nearly any cell in the body. A few cells from a drop of blood or from saliva on a cigarette butt are all detectives need to produce a DNA “fingerprint” of a criminal suspect.

**Apply** How does replication ensure each cell has a complete set of DNA?  

**MAIN IDEA**  
Proteins carry out the process of replication.

Although people may say that DNA copies itself, the DNA itself does nothing more than store information. Enzymes and other proteins do the actual work of replication. For example, some enzymes start the process by unzipping the double helix to separate the strands of DNA. Other proteins hold the strands apart while the strands serve as templates. Nucleotides that are floating free in the nucleus can then pair up with the nucleotides of the existing DNA strands. A group of enzymes called DNA polymerases (puh-LIM-muh-rays) bond the new nucleotides together. When the process is finished, the result is two complete molecules of DNA, each exactly like the original double strand.

**The Replication Process**

The following information describes the process of DNA replication in eukaryotes, which is similar in prokaryotes. As you read, follow along with each step illustrated in [FIGURE 3.1](#).

1. Enzymes begin to unzip the double helix at numerous places along the chromosome, called origins of replication. That is, the hydrogen bonds connecting base pairs are broken, the original molecule separates, and the bases on each strand are exposed. Like unzipping a suitcase, the process of unzipping DNA proceeds in two directions at the same time.

2. One by one, free nucleotides pair with the bases exposed as the template strands unzip. DNA polymerases bond the nucleotides together and form new strands complementary to each template. On one template, DNA replication occurs in a smooth, continuous way in one direction. This continuous strand is called the leading strand. On the other template, replication occurs in a discontinuous, piece-by-piece way in the opposite direction. Replication of this strand, known as the lagging strand, is not shown or described in detail here.

3. Two identical molecules of DNA result, each with one strand from the original molecule and one new strand. As a result, DNA replication is called semiconservative because one old strand is conserved, and one new strand is made.

**Infer** How does step 3 of replication show that DNA acts as a template?
When a cell’s DNA is copied, or replicated, two complete and identical sets of genetic information are produced. Then cell division can occur.

1. A DNA molecule unzips as nucleotide base pairs separate. Replication begins on both strands of the molecule at the same time.

The DNA molecule unzips in both directions.

2. Each existing strand of the DNA molecule is a template for a new strand. Free-floating nucleotides pair up with the exposed bases on each template strand. DNA polymerases bond these nucleotides together to form the new strands. The arrows show the directions in which new strands form.

3. Two identical double-stranded DNA molecules result from replication. DNA replication is semiconservative. That is, each DNA molecule contains an original strand and one new strand.

Two molecules of DNA

**CRITICAL VIEWING** How is each new molecule of DNA related to the original molecule?
In every living thing, DNA replication happens over and over again, 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. Instead, replication proceeds from hundreds of origins of replication along the chromosome, as shown in **Figure 3.2**, so the process takes just a few hours.

Another amazing feature of replication is that it has a built-in “proofreading” function to correct errors. Occasionally, the wrong nucleotide is added to the new strand of DNA. However, DNA polymerase can detect the error, remove the incorrect nucleotide, and replace it with the correct one. In this way, errors in replication are limited to about one error per 1 billion nucleotides.

Replication is happening in your cells right now. Your DNA is replicated every time your cells turn over, or replicate themselves. Your DNA has replicated trillions of times since you grew from a single cell.

**Infer** Why does a cell need to replicate its DNA quickly? TEKS 5A

**Figure 3.2** Eukaryotic chromosomes have many origins of replication. The DNA helix is unzipped at many points along each chromosome. The replication “bubbles” grow larger as replication progresses in both directions, resulting in two complete copies.

A
B
C
D

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**8.3 Formative Assessment**

**REVIEWING MAIN IDEAS**

1. Explain the function of replication. TEKS 5A
2. Explain how DNA serves as its own template during replication. TEKS 5A
3. How do cells help ensure that DNA replication is accurate? TEKS 5A

**CRITICAL THINKING**

4. Summarize. Describe two major functions of DNA polymerases. TEKS 9C
5. Infer. Why is it important that human chromosomes have many origins of replication? TEKS 5A
6. DNA is replicated before both mitosis and meiosis. How does the amount of DNA produced in a cell during mitosis compare with that produced during meiosis? TEKS 5A

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Transcription converts a gene into a single-stranded RNA molecule.

**Main Ideas**
- RNA carries DNA’s instructions.
- Transcription makes three main types of RNA.
- The transcription process is similar to replication.

**Connect to Your World**
Suppose you want to play Skee-Ball® at a game center, but the Skee-Ball lane takes tokens and you only have quarters. Do you go home in defeat? Do you stand idly by as someone else becomes high scorer? No, you exchange your quarters for tokens and then proceed to show the other players how it’s done. In a similar way, your cells cannot make proteins directly from DNA. They must convert the DNA into an intermediate molecule called RNA, or ribonucleic acid. That conversion process, called transcription, is the focus of this section.

**RNA carries DNA’s instructions.**

Soon after his discovery of DNA structure, Francis Crick defined the central dogma of molecular biology, which states that information flows in one direction, from DNA to RNA to proteins. The central dogma involves three processes, as shown in FIGURE 4.1.

- Replication, as you just learned, copies DNA (blue arrow).
- Transcription converts a DNA message into an intermediate molecule, called RNA (red arrow).
- Translation interprets an RNA message into a string of amino acids, called a polypeptide. Either a single polypeptide or many polypeptides working together make up a protein (green arrow).

In prokaryotic cells, replication, transcription, and translation all occur in the cytoplasm at approximately the same time. In eukaryotic cells, where DNA is located inside the nuclear membrane, these processes are separated both in location and time. Replication and transcription occur in the nucleus, whereas translation occurs in the cytoplasm. In addition, the RNA in eukaryotic cells goes through a processing step before it can be transported out of the nucleus. Unless otherwise stated, the rest of this chapter describes how these processes work in eukaryotic cells.

RNA acts as an intermediate link between DNA in the nucleus and protein synthesis in the cytoplasm. Like DNA, RNA, or ribonucleic acid, is a chain of nucleotides, each made of a sugar, a phosphate group, and a nitrogen-containing base. You can think of RNA as a temporary copy of DNA that is used and then destroyed.
RNA differs from DNA in three significant ways. First, the sugar in RNA is ribose, which has one additional oxygen atom not present in DNA’s sugar (deoxyribose). Second, RNA has the base uracil in place of thymine. Uracil, like thymine, forms base pairs with adenine. Third, RNA is a single strand of nucleotides, in contrast to the double-stranded structure of DNA. This single-stranded structure allows some types of RNA to form complex three-dimensional shapes. As a result, some RNA molecules can catalyze reactions much as enzymes do.

**Contrast** How do DNA and RNA differ?

**MAIN IDEA**  
**TEKS 4B, 6C, 9C**

**Transcription makes three main types of RNA.**

**Transcription** is the process of copying a sequence of DNA to produce a complementary strand of RNA. During the process of transcription, a gene—not an entire chromosome—is transferred into an RNA message. Just as replication is catalyzed by DNA polymerase, transcription is catalyzed by RNA polymerases, enzymes that bond nucleotides together in a chain to make a new RNA molecule. RNA polymerases are very large enzymes composed of many proteins that play a variety of roles in the transcription process.

**FIGURE 4.2** shows the basic steps of transcription in eukaryotic cells.

1. With the help of other proteins and DNA sequences, RNA polymerase recognizes the transcription start site of a gene. A large transcription complex consisting of RNA polymerase and other proteins assembles on the DNA strand and begins to unwind a segment of the DNA molecule, until the two strands separate from each other.

2. RNA polymerase, using only 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. The growing RNA strand hangs freely as it is transcribed, and the DNA helix zips back together.

3. Once the entire gene has been transcribed, the RNA strand detaches completely from the DNA. Exactly how RNA polymerase recognizes the end of a transcription unit is complicated. It varies with the type of RNA.

Transcription produces three major types of RNA molecules. Not all RNA molecules code for proteins, but most play a role in the translation process. Each type of RNA molecule has a unique function.

- **Messenger RNA (mRNA)** is an intermediate message that is translated to form a protein.
- **Ribosomal RNA (rRNA)** forms part of ribosomes, a cell’s protein factories.
- **Transfer RNA (tRNA)** brings amino acids from the cytoplasm to a ribosome to help make the growing protein.

Remember that the RNA strand must be processed before it can exit the nucleus of a eukaryotic cell. This step occurs during or just after transcription. However, we will next examine translation and then return to processing.

**Analyze** Explain why transcription occurs in the nucleus of eukaryotes. **TEKS 6C**
Transcription produces an RNA molecule from a DNA template. Like DNA replication, this process takes place in the nucleus in eukaryotic cells and involves both DNA unwinding and nucleotide base pairing.

1. A large transcription complex made of RNA polymerase and other proteins recognizes the start of a gene and begins to unwind the segment of DNA.

2. RNA polymerase uses one strand of the DNA as a template. RNA nucleotides form complementary base pairs with the DNA template. G pairs with C, and A pairs with U. The growing RNA strand hangs freely as it is transcribed. Then the DNA strand closes back together.

3. The completed RNA strand separates from the DNA template, and the transcription complex falls apart.

**CRITICAL VIEWING** Compare the nucleotide sequence of the RNA transcript with the nucleotide sequence of the nontemplate strand of DNA.
The transcription process is similar to replication.

The processes of transcription and replication share many similarities. Both processes occur within the nucleus of eukaryotic cells. Both are catalyzed by large, complex enzymes. Both involve unwinding of the DNA double helix. And both involve complementary base pairing to the DNA strand. In addition, both processes are highly regulated by the cell. Just as a cell does not replicate its DNA without passing a critical checkpoint, so, too, a cell carefully regulates which genes are transcribed into RNA.

The end results of transcription and replication, however, are quite different. The two processes accomplish very different tasks. Replication ensures that each new cell will have one complete set of genetic instructions. It does this by making identical sets of double-stranded chromosomes. This double-stranded structure makes DNA especially well suited for long-term storage because it helps protect DNA from being broken down and from potentially harmful interactions with other molecules. Replication occurs only once during each round of the cell cycle because each cell needs to make only one copy of its DNA.

In contrast, a cell may need hundreds or thousands of copies of certain proteins, or the rRNA and tRNA molecules needed to make proteins. Transcription enables a cell to adjust to changing demands. It does so by making a single-stranded complement of only a segment of DNA and only when that particular segment is needed. In addition, 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, as shown in Figure 4.3.

**Compare** How are the processes of transcription and replication similar? [TEKS 6C]

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**Formative Assessment**

**REVIEWING MAIN IDEAS**

1. What is the **central dogma**?
2. Why can the mRNA strand made during transcription be thought of as a mirror image of the DNA strand from which it was made? [TEKS 6C]
3. Why might a cell make lots of rRNA but only one copy of DNA? [TEKS 6C]

**CRITICAL THINKING**

4. **Apply** If a DNA segment has the nucleotides AGCCTAA, what would be the nucleotide sequence of the complementary RNA strand? [TEKS 6C]
5. **Synthesize** What might geneticists learn about genes by studying RNA?

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**CELL CYCLE**

6. A healthy cell cannot pass the G2 checkpoint until all of its DNA has been copied. Do you think that a cell must also transcribe all of its genes into RNA to pass this checkpoint? Explain. [TEKS 4B, 6C]
Translation

**KEY CONCEPT** Translation converts an mRNA message into a polypeptide, or protein.

**MAIN IDEAS**
- Amino acids are coded by mRNA base sequences.
- Amino acids are linked to become a protein.

**Connect to Your World**

As you know, translation is a process that converts a message from one language into another. For example, English words can be translated into Spanish words, into Chinese characters, or into the hand shapes and gestures of sign language. Translation occurs in cells too. Cells translate an RNA message into amino acids, the building blocks of proteins. But unlike people who use many different languages, all cells use the same genetic code.

**MAIN IDEA**

**TEKS 4B, 6C**

Amino acids are coded by mRNA base sequences.

**Translation** is the process that converts, or translates, an mRNA message into a polypeptide. One or more polypeptides make up a protein. The “language” of nucleic acids uses four nucleotides—A, G, C, and T in DNA; or A, G, C, and U in RNA. The “language” of proteins, on the other hand, uses 20 amino acids. How can four nucleotides code for 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.

**Triplet Code**

Different words have different numbers of letters. In the genetic code, however, all of the “words,” called codons, are made up of three letters. A codon is a three-nucleotide sequence that codes for an amino acid. Why is the genetic code read in units of three nucleotides? Well, we can’t entirely answer that question, but consider the possibilities. If one nucleotide coded for one amino acid, RNA could code for only four amino acids. If two nucleotides coded for one amino acid, RNA could code for 16 (4²) amino acids—still not enough. But if three nucleotides coded for one amino acid, RNA could code for 64 (4³) amino acids, plenty to cover the 20 amino acids used to build proteins in the human body and most other organisms.
As you can see in **Figure 5.1**, many amino acids are coded for by more than one codon. The amino acid leucine, for example, is represented by six different codons: CUU, CUC, CUA, CUG, UUA, and UUG. There is a pattern to the codons. In most cases, codons that represent the same amino acid share the same first two nucleotides. For example, the four codons that code for alanine each begin with the nucleotides GC. Therefore, the first two nucleotides are generally the most important in coding for an amino acid. As you will learn in Section 7, this feature makes DNA more tolerant of many point mutations.

In addition to codons that code for amino acids, three stop codons signal the end of the amino acid chain. There is also one start codon, which signals the start of translation and the amino acid methionine. This means that translation always begins with methionine. However, in many cases, this methionine is removed from the protein later in the process.

For the mRNA code to be translated correctly, codons must be read in the right order. Codons are read, without spaces, as a series of three nonoverlapping nucleotides. This order is called the reading frame. Changing the reading frame completely changes the resulting protein. It may even keep a protein from being made if a stop codon turns up early in the translation process. Therefore, punctuation—such as a clear start codon—plays an important role in the genetic code. **Figure 5.2** shows how a change in reading frame changes...
the resulting protein. When the mRNA strand is read starting from the first nucleotide, the resulting protein includes the amino acids arginine, tyrosine, and two serines. When the strand is read starting from the second nucleotide, the resulting protein includes aspartic acid, threonine, and valine.

**Common Language**
The genetic code is shared by almost all organisms—and even 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. With a few minor exceptions, almost all organisms follow this genetic code. As a result, the code is often called universal. The common nature of the genetic code suggests that almost all 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.

**Calculate** Suppose an mRNA molecule in the cytoplasm had 300 nucleotides. How many amino acids would be in the resulting protein?

**MAIN IDEA**

### Amino acids are linked to become a protein.

Let’s take a step back to look at where we are in the process of making proteins. You know mRNA is a short-lived molecule that carries instructions from DNA in the nucleus to the cytoplasm. And you know that this mRNA message is read in sets of three nucleotides, or codons. But how does a cell actually translate a codon into an amino acid? It uses two important tools: ribosomes and tRNA molecules, as illustrated in **Figure 5.3**.

Recall that ribosomes are the site of protein synthesis. Ribosomes are made of a combination of rRNA and proteins, and they catalyze the reaction that forms the bonds between amino acids. Ribosomes have a large and small subunit that fit together and pull the mRNA strand through. The small subunit holds onto the mRNA strand, and the large subunit holds onto the growing protein.

The tRNA acts as a sort of adaptor between mRNA and amino acids. You would need an adaptor to plug an appliance with a three-prong plug into an outlet with only two-prong openings. Similarly, cells need tRNA to carry free-floating amino acids from the cytoplasm to the ribosome. The tRNA molecules fold up in a characteristic L shape. One end of the L is attached to a specific amino acid. The other end of the L, called the anticodon, recognizes a specific codon. An **anticodon** is a set of three nucleotides that is complementary to an mRNA codon. For example, the anticodon CCC pairs with the mRNA codon GGG.
Translation converts an mRNA transcript into a polypeptide.
The process consists of three repeating steps.

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

2. The ribosome forms a peptide bond between the two amino acids and breaks the bond between the first tRNA and its amino acid.

3. The ribosome pulls the mRNA strand 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 recharge. The first site is again empty, exposing the next mRNA codon.

The ribosome continues to translate the mRNA strand until it reaches a stop codon. Then it releases the new protein and disassembles.

CRITICAL VIEWING The figure above shows how the first two amino acids are added to a growing protein. Draw a series of sketches to show how the next two amino acids are added. TEKS 4B, 6C
Translation, shown in **FIGURE 5.4**, has many steps and takes a lot of energy from a cell. It happens in the cytoplasm of both prokaryotic and eukaryotic cells. Before translation can begin, a small ribosomal subunit must bind to an mRNA strand in the cytoplasm. Next, a tRNA with methionine attached binds to the AUG start codon. This binding signals a large ribosomal subunit—which has three binding sites for tRNA molecules—to join. The ribosome pulls the mRNA strand through itself one codon at a time. As the strand moves, the start codon and its complementary tRNA molecule shift into the second site inside the large subunit. This shift leaves the first site empty, which exposes the next mRNA codon. The illustration shows the process in one ribosome, but in a cell many ribosomes may translate many mRNA molecules from the same gene at the same time.

1. The exposed codon attracts a complementary tRNA molecule bearing an amino acid. The tRNA anticodon pairs with the mRNA codon. This action brings the new tRNA molecule very close to the tRNA molecule occupying the second site.

2. Next, the ribosome helps form a peptide bond between the two amino acids. The ribosome then breaks the bond between the tRNA molecule in the second site and its amino acid.

3. The ribosome pulls the mRNA strand the length of one codon. The tRNA molecule in the second site is shifted into the third site, which is the exit site. The tRNA leaves the ribosome and returns to the cytoplasm to be charged with another amino acid. The tRNA molecule that was in the first site shifts into the second site. The first site is again empty, exposing the next mRNA codon. Another complementary tRNA molecule is attracted to the exposed mRNA codon, and the process continues. The ribosome moves down 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 falls apart.

**Summarize** Explain the different roles of the large and small ribosomal subunits.

**8.5 Formative Assessment**

**REVIEWING MAIN IDEAS**

1. Explain the connection between a **codon** and an amino acid.
2. Briefly describe how the process of **translation** is started. **TEKS 4B, 6C**

**CRITICAL THINKING**

3. **Synthesize** Suppose a tRNA molecule had the **anticodon** AGU. What amino acid would it carry?

4. **Hypothesize** The DNA of eukaryotic cells has many copies of genes that code for rRNA molecules. Suggest a hypothesis to explain why a cell needs so many copies of these genes.

5. **BIOCHEMICAL REACTIONS**

5. Enzymes have shapes that allow them to bind to a substrate. Some types of RNA also form specific three-dimensional shapes. Why do you think RNA, but not DNA, catalyzes biochemical reactions? **TEKS 9C**
Gene Expression and Regulation

**KEY CONCEPT** Gene expression is carefully regulated in both prokaryotic and eukaryotic cells.

**MAIN IDEAS**
- Prokaryotic cells turn genes on and off by controlling transcription.
- Eukaryotic cells regulate gene expression at many points.
- Environmental factors influence gene expression, resulting in different cell types.

**Connect to Your World**

Ours is a world of marvels. So many, in fact, that we may overlook what seem like little ones, such as plumbing. The turn of a handle sends clean water to your sink or shower. One twist and the water trickles out; two twists and it gushes forth. Another turn of the handle and the water is off again. But think about the mess and waste that would result if you couldn't control its flow. In a similar way, your cells have ways to control gene expression. Depending on an organism's needs, a gene can make a lot of protein, a little protein, or none at all.

**MAIN IDEA**

Prokaryotic cells turn genes on and off by controlling transcription.

The regulation of gene expression allows prokaryotic cells, such as bacteria, to better respond to stimuli and to conserve energy and materials. In general, this regulation is simpler in prokaryotic cells than in eukaryotic cells, such as those that make up your body. DNA in a prokaryotic cell is in the cytoplasm. Transcription and translation can happen at the same time. As a result, gene expression in prokaryotic cells is mainly regulated at the start of transcription.

A gene includes more than just a protein-coding sequence. It may have many other nucleotide sequences that play a part in controlling its expression. The start of transcription is largely controlled by these sequences, including promoters and operators. A promoter is a DNA segment that allows a gene to be transcribed. It helps RNA polymerase find where a gene starts. An operator is a DNA segment that turns a gene “on” or “off.” 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. 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. Operons are most often found in prokaryotes and roundworms. The lac operon was one of the earliest examples of gene regulation discovered in bacteria. It will serve as our example. The lac operon has three genes, which all code for enzymes that play a role in breaking down the sugar lactose. These genes are transcribed as a single mRNA transcript and are all under the control of a single promoter and
operator. This means that although we’re dealing with several genes, they act together as a unit.

The lac operon is turned on and off like a switch. When lactose is absent from the environment, the lac operon is switched off to prevent transcription of the lac genes and save the cell’s resources. When lactose is present, the lac operon is switched on to allow transcription. How does this happen?

Bacteria have a protein that can bind specifically to the operator. When lactose is absent, this 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.

**Without lactose** (switched off)

When lactose is present it binds to the repressor, which makes the repressor change shape and fall off the lac operon. RNA polymerase can then transcribe the genes in the lac operon. The resulting transcript is translated and forms three enzymes that work together to break down the lactose.

**With lactose** (switched on)

---

**Analyze** Explain how the lac operon is turned on or off like a switch.

**MAIN IDEA**  **TEKS** 5C, 6C, 6D

**Eukaryotic cells regulate gene expression at many points.**

You have already learned that every body cell in an organism has the same set of DNA. But your cells are not all the same. Cells differ from each other because different sets of genes are expressed in different types of cells. Eukaryotic cells can control the process of gene expression at many different points because of their internal compartments and chromosomal organization. As in prokaryotic cells, however, one of the most highly regulated steps is the start of transcription. In both cell types, RNA processing is a part of the transcription process. In eukaryotic cells, however, RNA processing also includes the removal of extra nucleotide segments from an mRNA transcript.
Starting Transcription

The start of transcription in eukaryotic cells is controlled by many elements that work together in complex ways. These elements include regulatory DNA sequences and proteins called transcription factors, as shown in **FIGURE 6.1**. They occur in different combinations in different types of cells. The interplay between these elements results in specialized cells and cell responses.

Eukaryotes have many types of regulatory DNA sequences. These sequences are recognized by transcription factors that bind to the DNA strand and help RNA polymerase know where a gene starts. Some DNA sequences, such as promoters, are close to the start of a gene. Others are far away from the genes they affect. However, DNA can loop and bend, bringing these sequences with their transcription factors into close contact with their target sequences.

Each gene has a unique combination of regulatory sequences. Some are found in almost all eukaryotic cells. For example, most eukaryotic cells have a seven-nucleotide promoter (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 and silencers also play a role by speeding up or slowing down, respectively, the rate of transcription of a gene.

Some genes control the expression of many other genes. Regulation of these genes is very important because they can have a large effect on development. One such gene codes for a protein called sonic hedgehog. This protein was first found in fruit flies, but many other organisms have very similar proteins that serve a similar function. Sonic hedgehog helps establish body pattern. When sonic hedgehog is missing in fruit flies, the embryos are covered with little prickles and fail to form normal body segments.

**mRNA Processing**

Another important part of gene regulation in eukaryotic cells is RNA processing, which is shown in **FIGURE 6.2**. The mRNA produced by transcription is similar to a rough cut of a film that needs a bit of editing. A specialized nucleotide is added to the beginning of each mRNA molecule, which forms a cap. It 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 helps the mRNA molecule exit the nucleus.
In eukaryotic cells, DNA contains noncoding stretches called introns and coding stretches called exons.

Protein-coding DNA is transcribed into mRNA.

mRNA goes through three major processing steps: the removal of introns and the addition of a cap and tail.

The exons are spliced together, and the mRNA molecule enters the cytoplasm, where it can be translated.

The “extra footage” takes the form of nucleotide segments that are not included in the final protein. In eukaryotes, exons are nucleotide segments that code for parts of the protein. Introns are nucleotide segments that intervene, or occur, between exons. Introns are removed from mRNA before it leaves the nucleus. The cut ends of the exons are then joined together by a variety of molecular mechanisms.

The role of introns is not clear. They may regulate gene expression. Or they may protect DNA against harmful mutations. That is, if large regions of DNA are noncoding “junk,” then mutations occurring in those regions will have no effect. Some mRNA strands can be cut at various points, resulting in different proteins. As a result, introns increase genetic diversity without increasing the size of the genome.

Apply Which parts of a gene are expressed as protein: introns or exons?

Environmental factors influence gene expression, resulting in different cell types.

Most multicellular organisms begin as a single fertilized egg cell, or zygote, which grows and divides into two cells. This process of growth and division repeats over and over. Cell differentiation is the process by which unspecialized cells develop into their mature forms and functions. Gene expression is responsible for the differentiation of cells. Gene expression is affected by both the internal and external environment. An organism's internal environment includes all the factors within the organism and its cells. The external environment refers to any factors outside the organism.
As cells grow and divide, subtle differences become more evident as distinct cell types are formed. During embryonic development, cell differentiation and cell growth form tissues and organs in a process called morphogenesis. FIGURE 6.3 shows the morphogenesis of embryonic eyes through the differentiation of cells.

**Internal Factors**

The differentiation of embryonic cells is based on several internal factors. First, the genetic make-up of the zygote provides the organism with many instructions for differentiation. A zygote’s genetic make-up includes all the genes that can be expressed within any cell of the organism, even after the organism has grown and developed. Genes that are expressed in the cells of a developing organism initiate cell differentiation.

Even before an egg cell is fertilized, the internal environment of the egg cell promotes differentiation. Proteins, mRNA, organelles, and other substances in the egg cell cytoplasm are not spread evenly throughout the egg cell, as shown in the unfertilized egg cell in FIGURE 6.4. After fertilization, as the zygote divides, the molecules in the cytoplasm are distributed unevenly among the different cells of the developing embryo. These molecules regulate gene expression in each cell and help determine what type of cell it will become.

Each cell in a developing embryo is influenced by other cells around it. In the developing eyes, for example, cells close to the optic vesicle are influenced to thicken and fold inward. These changes eventually lead to the development of the lens and cornea. Cells influence and communicate with each other by sending and receiving molecules that act as signals. Signals may also come from molecules embedded in the cell membrane. Signal molecules are proteins that induce a cell to follow a specific developmental path by causing a change in its gene expression. Signal molecules cause the expression of certain genes to be turned on or off. Some signal molecules can affect genes by preventing a gene from transcribing genetic information to mRNA. Gene expression also can be controlled after translation has occurred. For example, a protein may be produced by translation and then rapidly broken down by enzymes.
External Factors
Factors in an organism’s external environment also can affect gene expression. One such factor is the amount of oxygen cells receive from the atmosphere. Cells produce a complex transcription factor called HIF, which is made up of two proteins. HIF is involved in the differentiation of several tissues, especially in the pancreas. When there is abundant available oxygen, the cell makes both proteins but immediately breaks down one of them. Transcription cannot take place because both proteins are needed. However, when the cell senses that the amount of available oxygen is low, it does not break down the protein. With both proteins present, transcription can take place.

Temperature can influence gene expression in some organisms. The C gene in Himalayan rabbits is involved in development of the black color of fur, skin, and eyes. When the external temperature is above 35°C, the central parts of the rabbit’s body are over 30°C, and the gene is inactive. No pigments are produced, and the fur color is white. Below 20°C, the outer parts of the rabbit—such as the ears, tail, feet, and tip of the nose—are cooler, and the gene is expressed. These body parts are black.

The presence of drugs and chemicals in an organism’s external environment can also affect gene expression and cell differentiation. When magnesium chloride is present in the environment of certain fish embryos, they develop one eye instead of two. In the 1960s, the drug thalidomide was found to cause severe arm and leg deformities in human embryos. Children born from mothers who took this drug often had shortened and malformed limbs.

Light affects gene expression in Vanessa butterflies. If the immature caterpillars are placed in red light, the wings that develop in the adult butterflies are brightly colored. When the caterpillars are placed in green light, the adults have dark wings. Under blue light or in darkness, the wings are a pale color.

Identify Name two internal and two external factors that affect gene expression.

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<td><strong>5. DNA is loosely organized in areas where RNA polymerase is transcribing genes. What might you infer about a region of DNA that was loosely organized in muscle cells but tightly coiled in lung cells?</strong></td>
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<td>1. What is a promoter? <strong>TEKS 6D</strong></td>
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<td>2. In eukaryotic cells, genes each have a specific combination of regulatory DNA sequences. How do these combinations help cells carry out specialized jobs? <strong>TEKS 5C, 6D</strong></td>
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<td>3. <strong>Predict</strong> Suppose a bacterium had a mutated repressor protein that could not bind to the lac operator. How might this affect regulation of the operon? <strong>TEKS 6D</strong></td>
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<td>4. <strong>Summarize</strong> What are the three major steps involved in mRNA processing? <strong>TEKS 6C</strong></td>
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Mutations

**KEY CONCEPT** Mutations are changes in DNA that may or may not affect phenotype.

**MAIN IDEAS**
- Some mutations affect a single gene, while others affect an entire chromosome.
- Mutations may or may not affect phenotype.
- Mutations can be caused by several factors.

**Connect to Your World**

We all make mistakes. Some may be a bit embarrassing. Others become funny stories we tell our friends later. Still others, however, have far-reaching effects that we failed to see in our moment of decision. Cells make mistakes too. These mistakes, like our own, can have a range of effects. When they occur in DNA, they are called mutations, and cells have evolved a variety of methods for dealing with them.

**MAIN IDEA**

Some mutations affect a single gene, while others affect an entire chromosome.

You may already know the term *mutation* from popular culture, but it has a specific meaning in biology. A *mutation* is a change in an organism’s DNA. Many types of mutations can occur, as shown in FIGURE 7.2. Typically, mutations that affect a single gene happen during replication, whereas mutations that affect a group of genes or an entire chromosome happen during meiosis.

**Gene Mutations**

A *point mutation* is a mutation in which one nucleotide is substituted for another. That is, an incorrect nucleotide is put in the place of the correct nucleotide. Very often, such a mistake is caught and fixed by DNA polymerase. If it is not, the substitution may permanently change an organism’s DNA.

A *frameshift mutation* involves the insertion or deletion of a nucleotide in the DNA sequence. It usually affects a polypeptide much more than does a substitution. Frameshift mutations are so named because they shift the entire sequence following them by one or more nucleotides. To understand how this affects an mRNA strand, imagine a short sentence of three-letter “codons”:

**FIGURE 7.1** Cystic fibrosis (CF) is a genetic disease that is most commonly caused by a specific deletion. It causes the overproduction of thick, sticky mucus. Although CF cannot be cured, it is treated in a number of ways, including oxygen therapy (above).

**THE CAT ATE THE RAT**

If the letter *E* is removed, or deleted, from the first “THE,” all the letters that follow shift to the left. The sentence now reads:

**THC ATA TET HER AT . . .**
The sentence no longer makes sense. The same would be true if a nucleotide was added, or inserted, and all the letters shifted to the right. In the same way, a nucleotide sequence loses its meaning when an insertion or deletion shifts all the codons by one nucleotide. This change throws off the reading frame, which results in codons that code for different amino acids.

**Chromosomal Mutations**

Recall that during meiosis, homologous chromosomes exchange DNA segments through crossing over. If the chromosomes do not align with each other, these segments may be different in size. As a result, one chromosome may have two copies of a gene or genes, which is called gene duplication. The other chromosome may have no copy of the gene or genes. Gene duplication has happened again and again throughout eukaryotic evolution.

Translocation is another type of chromosomal mutation. In translocation, a piece of one chromosome moves to a nonhomologous chromosome. Translocations are often reciprocal, which means that the two nonhomologous chromosomes exchange segments with each other.

**Extract**

- Explain how a frameshift mutation affect reading frame? **TEKS** 6E
Mutations may or may not affect phenotype.

A mutation can affect an organism to different degrees. The effect depends on factors such as the number of genes involved and the location of the mutation.

**Impact on Phenotype**
Chromosomal mutations affect a lot of genes and tend to have a big effect on an organism. A mutation may break up a gene, which could make the gene no longer work, or it could make a new hybrid gene with a new function. Translocated genes may also come under the control of a new set of promoters, which could make many genes be more or less active than usual.

Gene mutations, though smaller in scale, can also have a big effect on an organism. Suppose a substitution occurs in a coding region of DNA that changes an AAG codon to CAG. The resulting protein will have a glutamine in place of a lysine. If this change happens in the active site of an enzyme, the enzyme may not be able to bind to its substrate. If the substituted amino acid differs from the original one in size or polarity, the mutation could affect protein folding and thus possibly destroy the protein’s function. A substitution could also result in a premature stop codon.

Even a mutation that occurs in a noncoding region can cause problems. For example, such a mutation could disrupt an mRNA splice site and prevent an intron from being removed. A mutation in a noncoding region could also interfere with the regulation of gene expression, keeping a protein from being produced or causing it to be produced all the time.

Many gene mutations, however, do not affect an organism’s phenotype. Remember that many codons code for the same amino acid. Therefore, some substitutions have no effect, especially those occurring in the third nucleotide of a codon. If AAG changes to AAA, the resulting protein still has the correct amino acid, lysine. A mutation that does not affect the resulting protein is called silent. Similarly, an incorrect amino acid might have little effect on a protein if it has about the same size or polarity as the original amino acid or if it is far from an active site. If a mutation occurs in a noncoding region, such as an intron, it may not affect the encoded protein at all.

**Impact on Offspring**
Mutations happen both in body cells and in germ cells. Mutations in body cells affect only the organism in which they occur. In contrast, mutations in germ cells may be passed to offspring. They are the underlying source of genetic variation, which is the basis of natural selection. Mutations in the germ line affect the phenotype of offspring. Often, this effect is so harmful that offspring do not develop properly or die before they can reproduce. Other mutations, though less severe, still result in less adaptive phenotypes. In such cases, natural selection removes these mutant alleles from the population. More rarely, a mutation results in a more beneficial phenotype. These mutations are favored by natural selection and increase in a population.

**Apply** Why aren’t mutations in body cells passed on to offspring?
Mutations can be caused by several factors.

Mutations are not uncommon, and organisms have many tools to repair them. However, events and substances can make mutations happen faster than the body’s repair system can handle.

**Replication Errors**

As you have learned, DNA polymerase has a built-in proofreading function. Nevertheless, a small number of replication errors are not fixed. They build up over time, and eventually affect how the cell works. For example, many studies suggest that mutations are a significant cause of aging.

**Mutagens**

Mutagens are agents in the environment that can change DNA. They speed up the rate of replication errors and, in some cases, even break DNA strands. Some mutagens occur naturally, such as ultraviolet (UV) rays in sunshine. Many others are industrial chemicals. Ecologists such as Rachel Carson, shown in **FIGURE 7.4**, warned the public about mutagens.

The human body has DNA repair enzymes that help find and fix mutations. For instance, UV light can cause neighboring thymine nucleotides to break their hydrogen bonds to adenine and bond with each other instead. Typically, one enzyme removes the bonded thymines, another replaces the damaged section, and a third bonds the new segment in place. Sometimes, these enzymes do not work. If these mistakes interfere with regulatory sites and control mechanisms, they may result in cancer. In rare cases, people inherit mutations that make their DNA repair systems less active, which makes these people very vulnerable to the damaging effects of sunlight.

Some cancer drugs take advantage of mutagenic properties by causing similar damage to cancer cells. One type of drug wedges its way between nucleotides, causing so many mutations that cancer cells can no longer function.

**Summarize** Explain why mutagens can damage DNA in spite of repair enzymes.

---

**Formative Assessment**

**REVIEWING MAIN IDEAS**

1. Explain why **frameshift mutations** have a greater effect than do **point mutations**. **TEKS 6E**
2. If GUA is changed to GUU, will the resulting protein be affected? Explain. **TEKS 6E**
3. Explain how **mutagens** can cause genetic **mutations** in spite of your body’s DNA repair enzymes. **TEKS 6E**

**CRITICAL THINKING**

4. **Connect** Some genetic mutations are associated with increased risk for a particular disease. Tests exist for some of these genes. What might be the advantages and disadvantages of being tested? **TEKS 6E**
5. **Illustrate** How could a mutated gene produce a shorter protein than that produced by the normal gene? Draw an example. **TEKS 6E**

**CONNECT TO ECOLOGY**

6. How might the presence of a chemical mutagen in the environment affect the genetic makeup and size of a population over time? **TEKS 7G, 7F**
8 Summary

**KEY CONCEPTS**

8.1 Identifying DNA as the Genetic Material
DNA was identified as the genetic material through a series of experiments. Griffith discovered a “transforming principle,” which Avery later identified as DNA. Hershey and Chase’s experiments with bacteriophages conclusively demonstrated that DNA is the genetic material.

8.2 Structure of DNA
DNA structure is the same in all organisms. DNA is a polymer made up of four types of nucleotides. Watson and Crick discovered that DNA consists of two strands of nucleotides bonded together into a double helix structure. Nucleotides always pair in the same way—C with G, and A with T.

8.3 DNA Replication
DNA replication copies the genetic information of a cell. During replication, a DNA molecule separates into two strands. Each strand serves as a template for building a new complementary strand through a rapid, accurate process involving DNA polymerase and other enzymes.

8.4 Transcription
Transcription converts a gene into a single-stranded RNA molecule. The transcription process is similar to DNA replication and makes three types of RNA. Messenger RNA is an intermediate molecule that carries DNA’s instructions to be translated.

8.5 Translation
Translation converts an mRNA message into a polypeptide, or protein. This process occurs on ribosomes, which are made of rRNA and proteins. Transfer RNA molecules bring amino acids to the growing protein by selectively pairing with mRNA codons.

8.6 Gene Expression and Regulation
Gene expression is carefully regulated in both prokaryotic and eukaryotic cells. In prokaryotes, transcription is the primary point of control. In eukaryotes, gene expression is controlled at many points, including RNA processing. Internal and external factors influence gene expression and cell differentiation.

8.7 Mutations
Mutations are changes in DNA that may or may not affect phenotype. Some mutations affect a single gene, and others affect an entire chromosome. Mutations may occur naturally, or they may be caused by mutagens. A mutation that does not affect phenotype is called a silent mutation. Mutations in sperm or egg cells can be passed to offspring.
Reviewing Vocabulary

Compare and Contrast

Describe one similarity and one difference between the two terms in each of the following pairs.

1. translation, transcription
2. point mutation, frameshift mutation
3. messenger RNA (mRNA), transfer RNA (tRNA)
4. codon, anticodon

Word Origins

5. The word codon was coined in 1962 by putting together the word code with the suffix -on, which means “a hereditary unit.” How do these word parts relate to the meaning of the term codon?

Use the word parts in this table to answer the next two questions.

<table>
<thead>
<tr>
<th>Part</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-gen</td>
<td>to give birth</td>
</tr>
<tr>
<td>muta-</td>
<td>to change</td>
</tr>
<tr>
<td>phago-</td>
<td>eating</td>
</tr>
<tr>
<td>poly-</td>
<td>many</td>
</tr>
</tbody>
</table>

6. Use the meaning of the word parts to write your own definitions for the following terms: mutagen, bacteriophage, polypeptide.

7. Suggest a likely definition for these biology terms: polygenic, phagocyte.

Reviewing MAIN IDEAS

8. How did qualitative, chemical, and enzyme tests help Avery identify DNA as the transforming principle? [TEKS 3F]

9. Hershey and Chase confirmed that DNA, not protein, was the genetic material. How do the results of their two experiments support this conclusion? [TEKS 3F, 6A]

10. Describe Watson and Crick’s double helix DNA model. Include a labeled drawing of the model. [TEKS 3F, 6A]

11. One DNA strand has the nucleotide sequence AACGTA. What is the sequence of the other strand? [TEKS 6A]

12. How do the base pairing rules explain how a strand of DNA acts as a template during replication? [TEKS 5A]

13. What are three main steps in DNA replication? [TEKS 5A]

14. What does it mean to say that there is a “proofreading” function in DNA replication? [TEKS 5A]

15. Describe two differences between DNA and RNA.

16. List the main types of RNA and their functions.

17. Explain the process of mRNA codons and tRNA anticodons coding for a specific amino acid. [TEKS 4B]

18. What role do ribosomes play in translation? [TEKS 6C]

19. Where in the eukaryotic cell do replication, transcription, RNA processing, and translation each occur?

20. How do the promoter and operator work together to control gene expression? [TEKS 6D, 9C]

21. Describe mRNA processing in eukaryotic cells. [TEKS 6D]

22. Describe three ways mutations can occur. [TEKS 6E]
Critical Thinking

23. Identify Give one example of how a mutation may affect an organism’s traits, and one example of how a mutation may not affect an organism’s traits. [TEKS] 6E

24. Describe Explain the roles of DNA, RNA, and environmental factors in gene expression and cell differentiation. [TEKS] 5C

25. Hypothesize If the nucleus were surrounded by a membrane that had fewer pores than usual, how might the rate of protein synthesis be affected, and why?

26. Illustrate For the DNA sequence TACCAAGTGAAAATT, write the sequence of its RNA transcript and the sequence of amino acids for which it codes. Write the sequence of its RNA transcript to illustrate an example of a point mutation. [TEKS] 6E

27. Predict Suppose you genetically altered a gene in a line of eukaryotic cells by inserting only the operator from the bacterial lac operon. Would adding lactose to the cell culture cause the cells to start transcribing the altered gene? Explain your reasoning. [TEKS] 6D, 9C

28. Contrast 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? [TEKS] 3F

29. Recognize Why was it difficult for scientists to be convinced that DNA was the genetic material common to all organisms? [TEKS] 6B

30. Synthesize Watson and Crick learned from Franklin’s x-ray crystallography that the distance between the backbones of the DNA molecule was the same for the length of the molecule. How did this information, combined with what they knew about the four base sizes, lead to their model of DNA structure? [TEKS] 3F

Interpreting Visuals

Use the diagram to answer the next three questions.

31. Apply What process is taking place in this diagram? [TEKS] 4B, 5A

32. Apply What do the arrows on the yellow strands indicate? [TEKS] 5A

33. Predict If you were to extend the diagram in both directions, what would you expect to see? [TEKS] 5A

Analyzing Data Interpret a Histogram

Many factors contribute to breast cancer, including some that are genetic. For example, women with a mutation in the BRCA1 gene have an especially high risk of developing breast cancer. The histogram below shows the total estimated number of new breast cancer cases for women in the United States for 2003. Use the data in the histogram to answer the next two questions.

ESTIMATED NEW CASES OF BREAST CANCER

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Estimated number</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;30</td>
<td>500</td>
</tr>
<tr>
<td>30–39</td>
<td>6000</td>
</tr>
<tr>
<td>40–49</td>
<td>9000</td>
</tr>
<tr>
<td>50–59</td>
<td>12,000</td>
</tr>
<tr>
<td>60–69</td>
<td>15,000</td>
</tr>
<tr>
<td>70–79</td>
<td>18,000</td>
</tr>
<tr>
<td>&gt;80</td>
<td>20,000</td>
</tr>
</tbody>
</table>

Source: American Cancer Society

34. Analyze In which age group was the incidence of new cases the lowest? the highest?

35. Hypothesize Using the data in this histogram, develop a hypothesis to explain why breast cancer genes are still present in the population.

Making Connections

36. Write an Analogy This chapter includes an analogy about exchanging quarters for tokens at a game center to represent the process of transcription. Think of your own analogy for one of the processes you learned about in this chapter. Write a paragraph using that analogy to explain the process. Also, note any limitations of your analogy. (That is, in what ways does it not “fit” the process you’re explaining?) [TEKS] 4B, 6C

37. Synthesize Look again at the picture of the glowing mouse on the chapter opener. The gene for the protein GFP was inserted into a mouse egg, and then expressed in the mouse. What genetic processes are involved in the expression of this gene? [TEKS] 6D
### MULTIPLE CHOICE

**TEKS 5C**

1. Cell specialization results from interactions between regulatory DNA sequences and proteins called transcription factors. What is the role of DNA regulatory sequences in cells?
   - A. They cause all of the genes in a cell to be expressed.
   - B. They prevent transcription from taking place.
   - C. They identify the start of a gene for RNA polymerase so transcription can occur.
   - D. They prevent homeobox genes from being expressed.

**TEKS 3A, 6A**

2. Before the genetic code could be understood, scientists needed to know that a codon is composed of three nucleotides. This situation is an example of the —
   - A. scientists making inferences based on data
   - B. cumulative nature of scientific evidence
   - C. way that theories can lead to scientific laws
   - D. ability of scientists to make hypotheses

**TEKS 2G, 6C**

3. The illustration above shows a strand of mRNA and the complementary tRNA molecules that can base pair with the mRNA codons. What is the correct sequence of amino acids?
   - A. lys-his-tyr
   - B. his-tyr-lys
   - C. tyr-lys-his
   - D. lys-tyr-his

**TEKS 2G, 6E**

4. Less than 60% of the DNA sequence of the human GM-CSF gene and the mouse GM-CSF gene is the same. When scientists put the human gene into mice, however, it functions properly. Which statement best explains why this happens?
   - A. The resulting proteins are similar enough.
   - B. Each gene codes for a different protein.
   - C. The human DNA sequence undergoes a mutation once placed into mice.
   - D. Both DNA sequences must produce identical strands of RNA.

**THINK THROUGH THE QUESTION**

The name of the gene is not important in answering this question. Recognize that the question involves only one type of gene. Don’t let a complicated name distract you from answering the real question.

**TEKS 2G, 6E**

5. The diagram above shows the nucleotides making up a segment of DNA. Which diagram below illustrates the type of change in the DNA characterized as a frameshift insertion mutation?
   - A. 
   - B. 
   - C. 
   - D. 

The diagram above shows a segment of DNA. Which diagram below illustrates the type of change in the DNA characterized as a frameshift insertion mutation?