CHAPTER 14

RNA and Protein Synthesis

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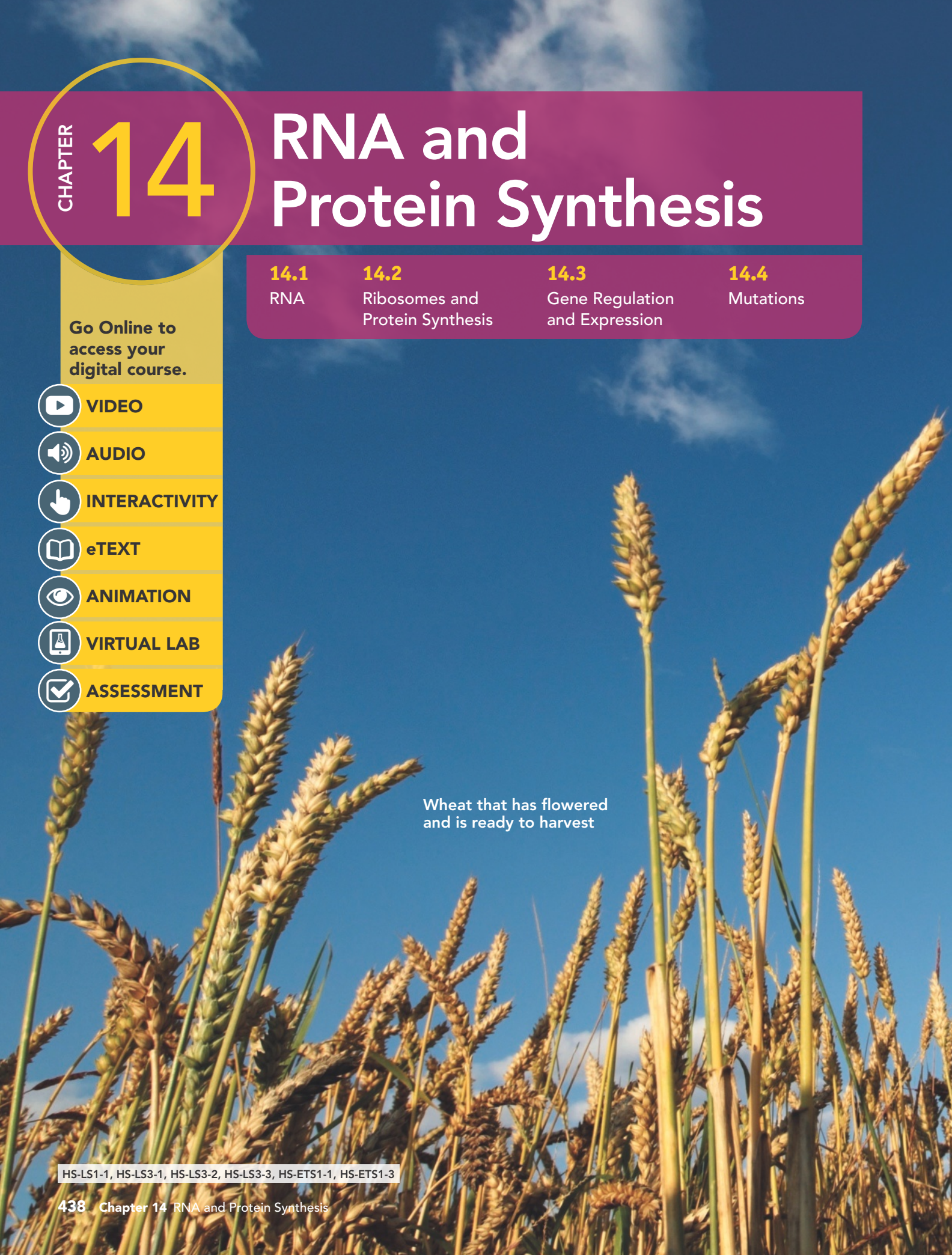


Wheat that has flowered and is ready to harvest

HS-LS1-1, HS-LS3-1, HS-LS3-2, HS-LS3-3, HS-ETS1-1, HS-ETS1-3

CASE STUDY

How does a plant remember winter?

Winters on the prairies of the northern Great Plains can be long, cold, and brutal. When spring does come, the growing season is shorter than it is farther south, and that presents special challenges to farmers in states like North Dakota and South Dakota. They need crops that will sprout early in the spring, grow quickly, and produce a high yield.

One of the most important crops in these states is wheat. Wheat serves as a source of grain for flour to make bread, pasta, and other foods. For American farmers, wheat is a major cash crop, and is widely exported throughout the world. However, for many farmers in the northern Great Plains, the planting time for wheat is not in the spring, as you might expect.

Rather, many farmers plant a variety of wheat called "winter wheat" in September or early October. These plants sprout before the first frost and then lay dormant all winter, enduring snowstorms and extreme low temperatures. In springtime, the plants grow quickly to maturity, flower (That's right, wheat plants produce flowers!), and produce excellent yields of grain.

There are many advantages to winter wheat. One advantage is high productivity. Another advantage is the ability to evade insect pests, since the planting is done in the fall when many such pests have disappeared for the winter.

The varieties developed for winter wheat have a very interesting property. Unless they endure an extended, very cold winter, they will not produce flowers in the spring and therefore will not produce grain. In a sense, the plants are able to "remember" winter, and will not go to flower until they have passed through it. If these varieties of winter wheat are planted in year-round warm climates, they do not flower and produce grain.

How do they do this? Plants like winter wheat hold back on activating the genes needed for flowering until they have lived through a cold season. As we will see, this involves the control of gene expression by a mechanism known as epigenetics. Plants, unlike animals, don't have nervous systems, and they certainly don't "remember" seasons in the way that you or I might. So, how can a plant know that winter has passed and adjust the expression of its genes to produce flowers in the spring?

Throughout this chapter, look for connections to the CASE STUDY to help you answer this question.

LESSON 14.1

RNA

KEY QUESTIONS

- *How does RNA differ from DNA?*
- *How does the cell make RNA?*

HS-LS1-1: Construct an explanation based on evidence for how the structure of DNA determines the structure of proteins which carry out the essential functions of life through systems of specialized cells.

HS-LS3-1: Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring.

VOCABULARY

RNA
messenger RNA
ribosomal RNA
transfer RNA
transcription
RNA polymerase
promoter
intron
exon

READING TOOL

As you read, identify the similarities and differences between RNA and DNA. Complete the Venn diagram in your **Biology Foundations Workbook.**

Once it was clear that DNA was the genetic material, biologists realized that it must contain a code that living cells can read, understand, and express. But what sort of code? DNA is made of just four nucleotides joined together in double-stranded molecules that may be millions of bases in length. What exactly do those bases code for, and how does the cell "read" that code? That's where RNA comes in.

The Role of RNA

When Watson and Crick solved the double-helix structure of DNA, they realized that the structure itself did not explain how a gene works. Eventually, scientists learned that another nucleic acid, ribonucleic acid, or RNA, helped to put the genetic code into action. **RNA**, like DNA, is a nucleic acid that consists of a long chain of nucleotides.

In a general way, genes contain coded DNA instructions that tell cells how to build proteins. The first step in decoding these genetic instructions is to copy part of the base sequence from DNA into RNA. RNA then uses these instructions to direct the production of proteins, which help to determine an organism's characteristics.

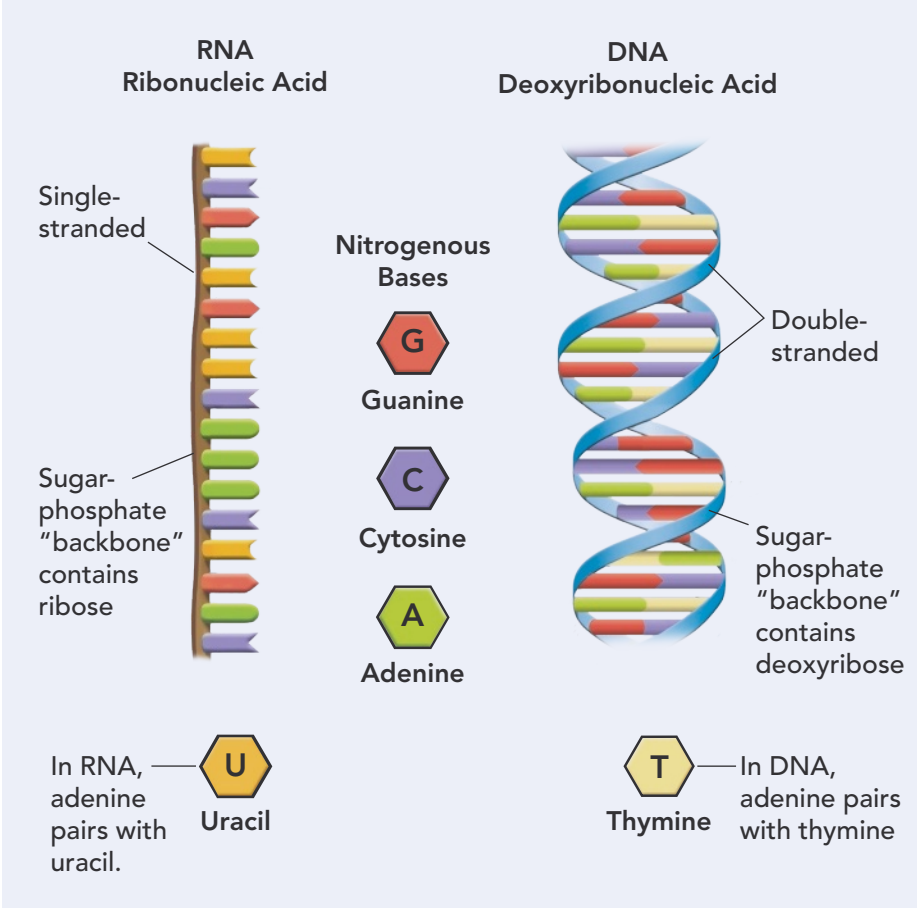
Comparing RNA and DNA

Like DNA, RNA is made up of nucleotides. Each nucleotide consists of a 5-carbon sugar, a phosphate group, and a nitrogenous base. However, DNA and RNA differ in three important ways. ***Unlike DNA, RNA uses the sugar ribose instead of deoxyribose, RNA generally is single stranded, and RNA contains uracil in place of thymine.*** These chemical differences make it easy for enzymes in the cell to tell DNA and RNA apart. The structures of DNA and RNA are shown in **Figure 14-1**.

Figure 14-1

Comparing RNA and DNA

Although the two molecules are similar, the differences between DNA and RNA allow them to perform separate functions in the cell. The information in DNA is always around, stored in the nucleus. In contrast, RNA is synthesized when the products of a particular gene are needed.



You can compare the different roles played by DNA and RNA to the two types of plans used by builders. DNA is a bit like an architect's master plan. It has all the information needed to construct a building. But builders never bring the valuable master plan to the job site, where it might be damaged or lost. Instead, they work from blueprints, which are inexpensive, disposable copies of the master plan.

INTERACTIVITY

Compare the structures of RNA and DNA and learn how RNA is used to create proteins.

In the cell, the DNA "master plan" remains safe in the cell's nucleus, where it serves as a template to make multiple RNA copies. Then those RNA "blueprints" travel to the ribosomes, which then put the coded instructions into action by assembling proteins in the cytoplasm.

READING CHECK Summarize What is the role of RNA in the production of proteins?

VIDEO

Explore the phenomenon of reverse transcription using viruses and learn how AZT can be used to interfere with this process in HIV.

Three Main Types of RNA

You can think of an RNA molecule as a working copy of a gene, which is a functional segment of DNA. RNA has many roles, but for now, we will focus on just one role, which is protein synthesis. RNA controls the assembly of amino acids into proteins.

There are three main types of RNA involved in protein synthesis: messenger RNA, ribosomal RNA, and transfer RNA. Like workers in a factory, each type of RNA molecule specializes in a different aspect of the job.

Messenger RNA (mRNA) Most genes encode instructions for assembling amino acids into proteins. The molecules of RNA that carry copies of these instructions from the nucleus to ribosomes in the cytoplasm are known as **messenger RNA** (mRNA).

Ribosomal RNA (rRNA) Proteins are assembled on ribosomes, which are small organelles composed of two subunits. The subunits are made of several **ribosomal RNA** (rRNA) molecules and as many as 80 different proteins.

Transfer RNA (tRNA) During the assembly of a protein, a third type of RNA molecule carries amino acids to the ribosome and matches them to the coded mRNA message. These molecules are known as **transfer RNA** (tRNA).

READING CHECK **Describe** List the three main types of RNA and their functions.

HS-LS1-1

Quick Lab Open-Ended Inquiry

How Can You Model DNA and RNA?

1. Work with a partner or in a group to plan models of DNA and RNA. Plan to use available materials, such as beads, toothpicks, or modeling clay. You could also choose to draw a diagram or make a computer model.
2. Have your teacher review your plan before you proceed.
3. Carry out your plan. Begin by making the model of DNA. Then use one of the DNA strands as a template to make the model of RNA.

ANALYZE AND CONCLUDE

1. **Evaluate Models** How well do the models represent DNA and RNA? What are the limitations of the models?
2. **Use Models** How does DNA act to specify a molecule of RNA? Use your model to help demonstrate this process.
3. **Synthesize Information** Construct a graphic organizer to compare and contrast the chemical structure, properties, and functions of DNA and RNA.

RNA Synthesis

A single DNA molecule may contain hundreds or even thousands of genes. However, only those genes being expressed are copied into RNA at any given time.

READING TOOL

After you read this section, write down the steps of RNA synthesis in the order in which they occur. Re-read the section and check your work.

Transcription

The process of copying a base sequence from DNA to RNA is known as **transcription**. Transcription is similar to DNA replication, but the product is an RNA molecule instead of a duplicate of DNA. ***In transcription, segments of DNA serve as templates to produce complementary RNA molecules.*** As shown in **Figure 14-2**, transcription is carried out by an enzyme called **RNA polymerase**. RNA polymerase first binds to DNA and separates the DNA strands. It then uses one strand of DNA as a template to assemble nucleotides into a complementary strand of RNA. The ability to quickly copy a DNA sequence into RNA makes it possible for a single gene to produce hundreds, or even thousands, of RNA molecules.

Promoters

How does RNA polymerase know where to start and stop making a strand of RNA? The answer is that RNA polymerase does not bind to DNA just anywhere. The enzyme binds only to **promoters**, which are regions of DNA with specific base sequences that can bind to RNA polymerase. Other regions of DNA cause transcription to stop when an RNA molecule is completed.

INTERACTIVITY

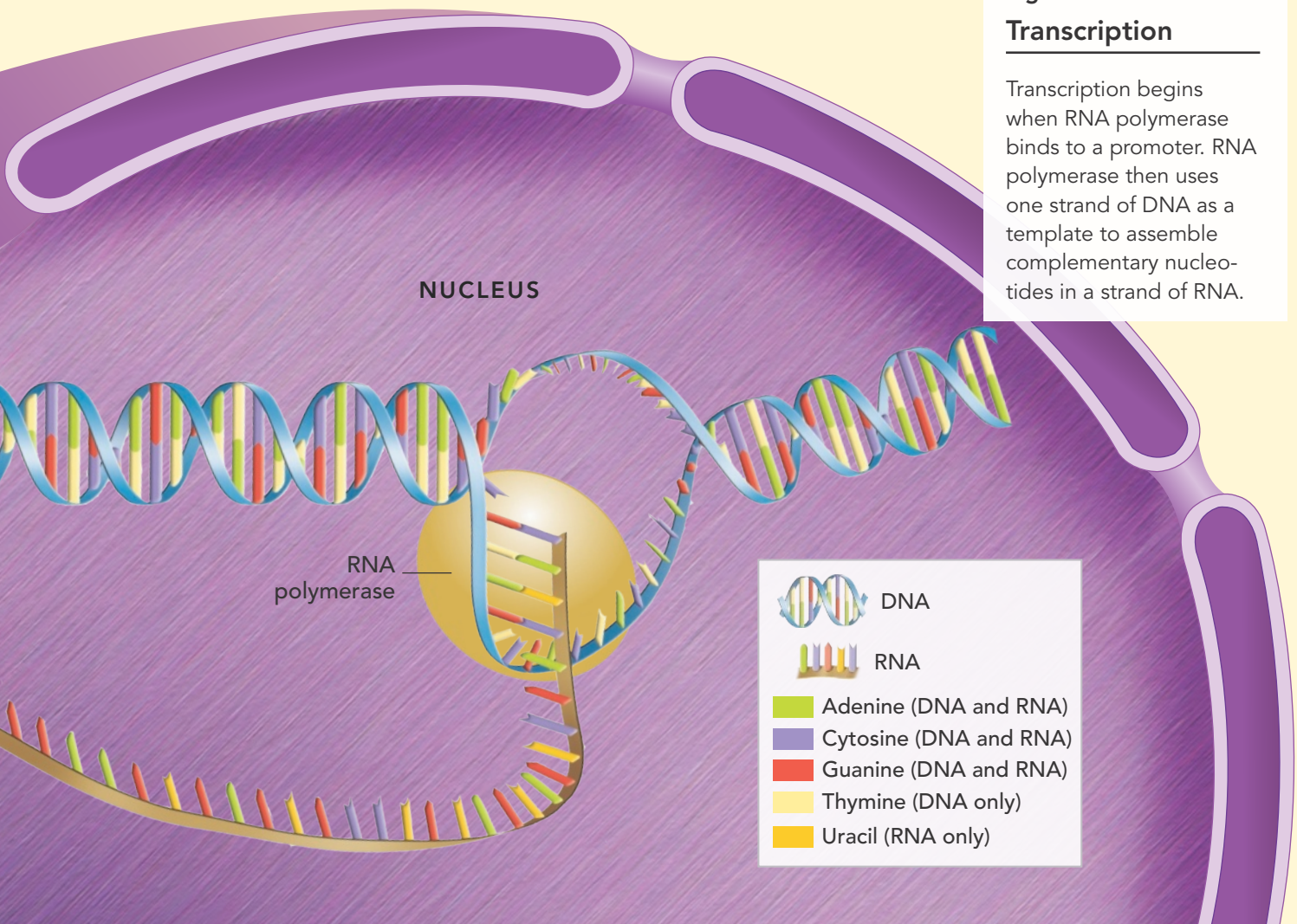


Figure 14-2

Transcription

Transcription begins when RNA polymerase binds to a promoter. RNA polymerase then uses one strand of DNA as a template to assemble complementary nucleotides in a strand of RNA.

BUILD VOCABULARY

Academic Words The word splice means to "join together." When the introns are removed, the exons are joined together.

RNA Editing Like a writer's first draft, new RNA molecules sometimes require a bit of editing before they are ready to be read. These pre-mRNA molecules have bits and pieces cut out of them before they can go into action. The portions that are cut out and discarded are called **introns**. In eukaryotes, introns are taken out of newly synthesized pre-mRNA molecules while they are still in the nucleus. The remaining pieces, known as **exons**, are then spliced back together to form the final mRNA, as shown in **Figure 14-3**.

What is the purpose of making a large RNA molecule and then throwing parts of that molecule away? That's a good question, and biologists still don't have a complete answer. Some pre-mRNA molecules are cut and spliced in different ways in different tissues. Because of this, a single gene can actually produce several different mRNA molecules. Introns and exons may also play a role in evolution, making it possible for very small changes in DNA sequences to have dramatic effects on how genes affect cellular function.

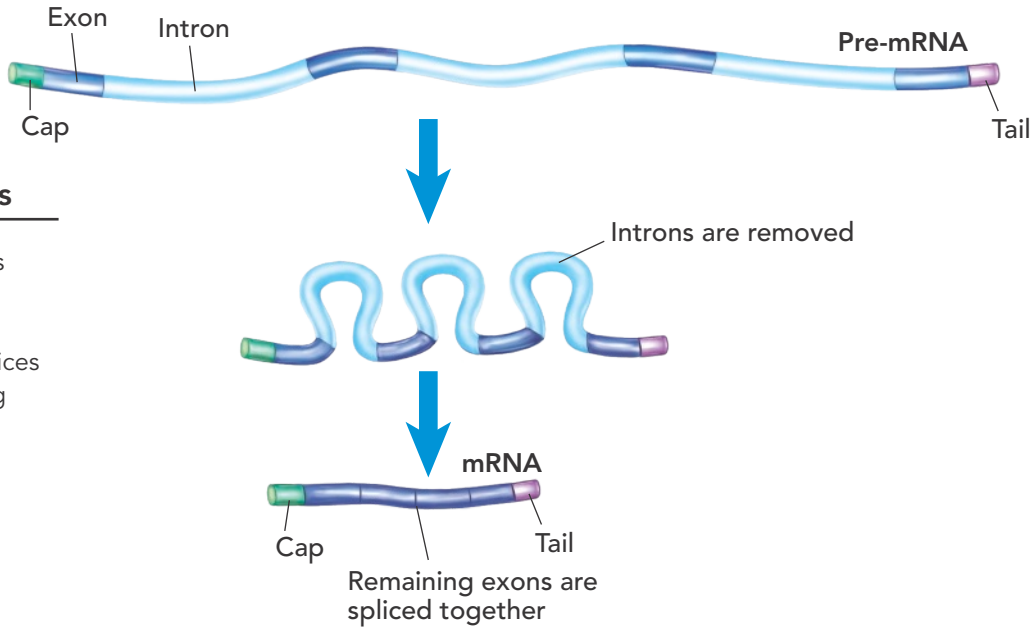


Figure 14-3

Introns and Exons

Like editing out scenes from a movie, the cell removes introns from pre-mRNA. Then it splices together the remaining pieces, called exons.

HS-LS1-1, HS-LS3-1

LESSON 14.1 Review

KEY QUESTIONS

1. How are RNA and DNA similar? How do they differ?
2. How is the information in DNA passed to a molecule of mRNA? Describe this process.

CRITICAL THINKING

3. **Construct an Explanation** How does the cell use both DNA and RNA to direct protein synthesis?
4. **Infer** Why are regions called promoters essential to RNA transcription?
5. **Infer** Why is it important for a single gene to be able to produce hundreds or thousands of the same RNA molecules?
6. **CASE STUDY** From what you have learned so far about DNA and RNA, what can you conclude about the role of RNA in the flowering of winter wheat? What questions do you still have?

Ribosomes and Protein Synthesis

LESSON 14.2

KEY QUESTIONS

- *How does the genetic code work?*
- *What role does the ribosome play in assembling proteins?*
- *How does molecular biology relate to genetics?*

HS-LS1-1: Construct an explanation based on evidence for how the structure of DNA determines the structure of proteins which carry out the essential functions of life through systems of specialized cells.

HS-LS3-1: Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring.

Think of a molecule of mRNA as containing a secret code written in just four letters: A, C, G, and U. How would you go about decoding the hidden message? That's the problem every cell solves as it uses the code in mRNA to build proteins, one amino acid after another.

The Genetic Code

As you have read, the first step in the process of decoding genetic messages is transcription, which is the copying of a nucleotide base sequence from DNA to mRNA. The next steps lead to the assembly of a protein. Proteins are made by joining amino acids together into chains called **polypeptides**. Twenty different amino acids are commonly found in polypeptides.

The specific order in which amino acids are joined together in a polypeptide chain determines the shape, chemical properties, and ultimately, function of a protein. How is the order of bases in DNA and RNA molecules translated into the order of amino acids in a polypeptide?

The four bases of RNA form a kind of language with just four letters: A, C, G, and U. We call this language the **genetic code**. How can a code with just four letters carry the instructions for 20 different amino acids? ***The genetic code is read three bases at a time. Each "word" of the code is three bases long and corresponds to a single amino acid.*** This three-base "word" is known as a codon. A **codon** consists of three consecutive bases that specify a single amino acid to be added to the polypeptide chain.

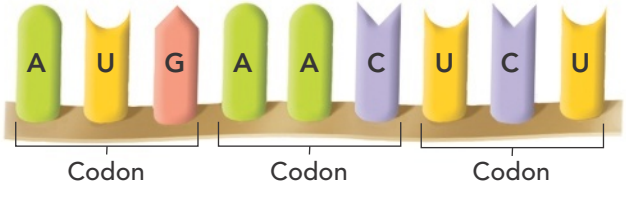


Figure 14-4

Codons

A codon is a group of three nucleotide bases in messenger RNA that specifies a particular amino acid.

VOCABULARY

polypeptide
genetic code
codon
translation
anticodon

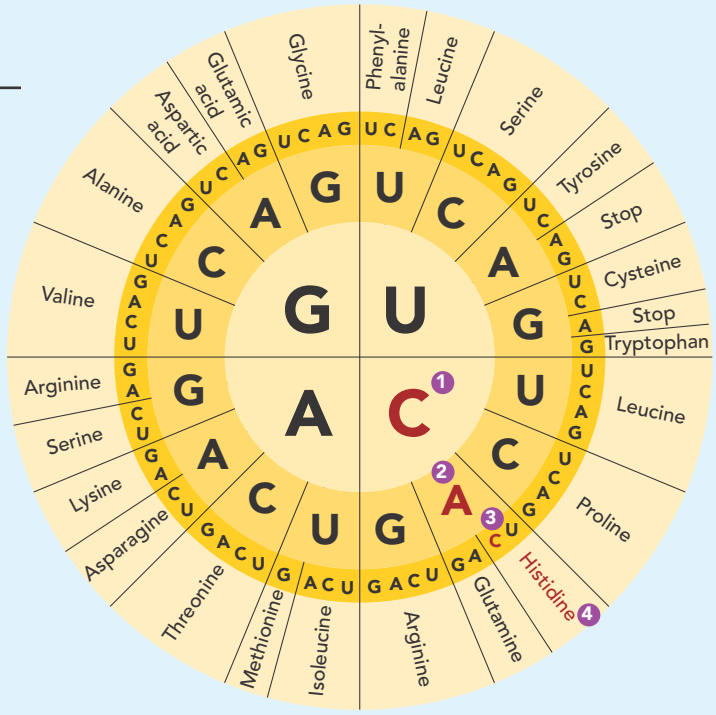
READING TOOL

As you read, identify the steps of translation and protein synthesis. Create a flowchart in your **Biology Foundations Workbook.**

Figure 14-5

The Genetic Code

To interpret this diagram, read each codon from the inner circle to the outer circle. For example, the codon CAC codes for the amino acid called histidine. **Use Models** Which two codons code for glutamic acid?



BUILD VOCABULARY

Academic Words The verb specify means "to identify precisely." Each codon in the genetic code specifies the next amino acid to add to a polypeptide. Three "stop" codons specify when no amino acids should be added, and synthesis should cease.

INTERACTIVITY

Explore the genetic code.

How to Read Codons

Because there are four different bases in RNA, there are 64 possible three-base codons ($4 \times 4 \times 4 = 64$) in the genetic code. Most amino acids can be specified by more than one codon. For example, six different codons—UUA, UUG, CUU, CUC, CUA, and CUG—specify leucine. But only one codon—UGG—specifies the amino acid tryptophan.

You can use **Figure 14-5** to interpret all 64 codons. Start at the middle of the circle with the first letter of the codon. Move out to the second ring to find the second letter of the codon. Then find the third and final letter among the smallest set of letters in the third ring from the center. Next to the third letter is the amino acid that the codon specifies.

Start and Stop Codons

Whether a message is communicated in writing or the genetic code, it needs punctuation marks. In English, punctuation tells us where to pause, when to sound excited, and where to start and stop a sentence. The genetic code has punctuation marks, too. The methionine codon AUG also serves as the initiation, or "start," codon for protein synthesis. Following the start codon, mRNA is read, three bases at a time, until it reaches one of three different "stop" codons, which end translation. At that point, the polypeptide is complete.

READING CHECK **Interpret Diagrams** Refer to **Figure 14-5**. What does the codon GAC code for?

Analyzing Data

Crack the Code

The middle of an mRNA molecule contains the nucleotide sequence shown here. Much more of the mRNA is translated. Assume that the sequence is translated from left to right.

AUUUAACUGUUCUGUCUAGAG

1. **Construct an Explanation** Based only on the information provided, why could the mRNA section be translated into three different sets of amino acids, instead of just one set?
2. **Use Models** Use the genetic code to translate the sequence into each of the three possible sets of amino acids.

3. **Draw Conclusions** Which of the three sets of amino acids is the most likely to be included in the polypeptide? Explain your reasoning.

Translation

You can think of the sequence of bases in an mRNA molecule as a set of instructions. The sequence gives the order in which amino acids should be joined to produce a polypeptide. Once the polypeptide is complete, it then folds into its final shape or joins with other polypeptides to become a functional protein.

If you've ever assembled a complex toy, you know that just reading the instructions is only the first step. You need to follow the instructions to put the parts together. A cell part that acts like a tiny factory—the ribosome—carries out the assembly tasks. ***Ribosomes use the sequence of codons in mRNA to assemble amino acids into polypeptide chains.*** The decoding of an mRNA message into a protein is a process known as **translation**.

Steps in Translation Translation begins when a ribosome attaches to an mRNA molecule in the cytoplasm. As each codon passes through the ribosome, several molecules of tRNA bring the proper amino acids into the ribosome. One at a time, the ribosome then attaches these amino acids to the growing chain. Each tRNA molecule carries just one kind of amino acid. In addition, each tRNA molecule has three unpaired bases that are together called an **anticodon**. Each anticodon is complementary to a codon on mRNA. In the case of the tRNA molecule for methionine, the anticodon is UAC, which pairs with the methionine codon, AUG.

The ribosome has a second binding site for a tRNA molecule for the next codon. If that next codon is UUC, a tRNA molecule with an AAG anticodon fits against the mRNA molecule held in the ribosome. That second tRNA molecule brings the amino acid phenylalanine into the ribosome.

INTERACTIVITY

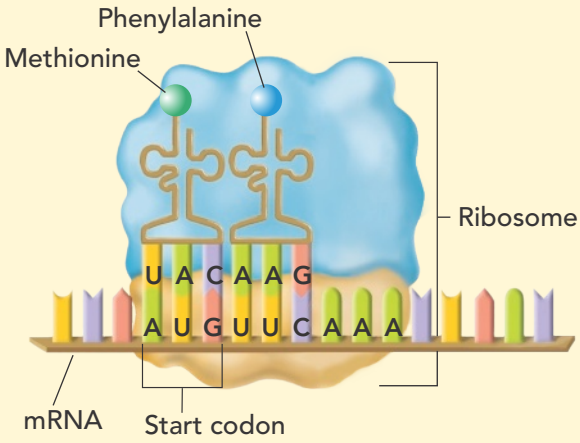
Perform a virtual activity to explore the role of mRNA in protein synthesis.

ANIMATION

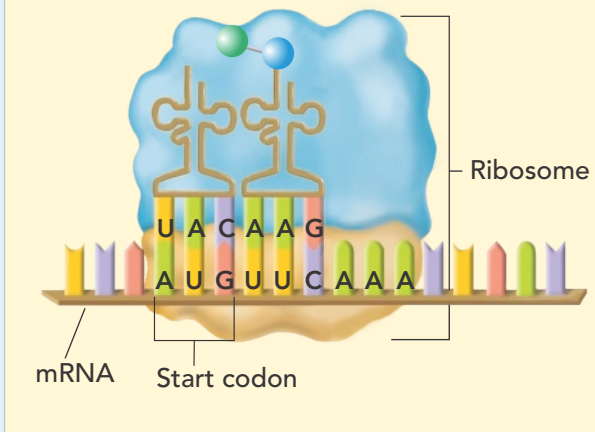
hhmi | BioInteractive

Figure 14-6 Translation

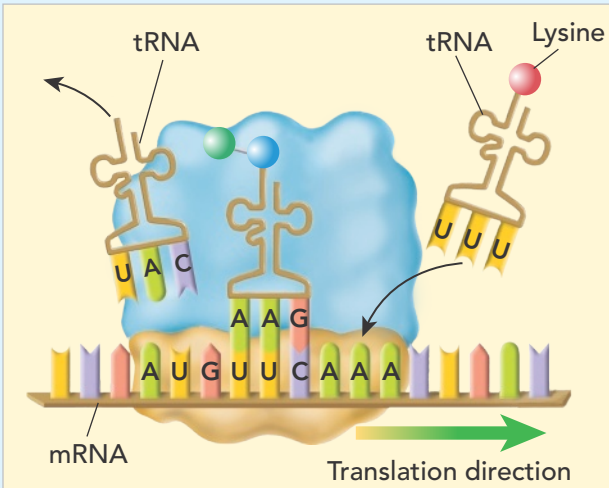
All three types of RNA interact at a ribosome to form a polypeptide. A molecule of mRNA binds to the ribosome, which is made of rRNA. Then molecules of tRNA bring amino acids. The numbered diagrams show the process of translation.



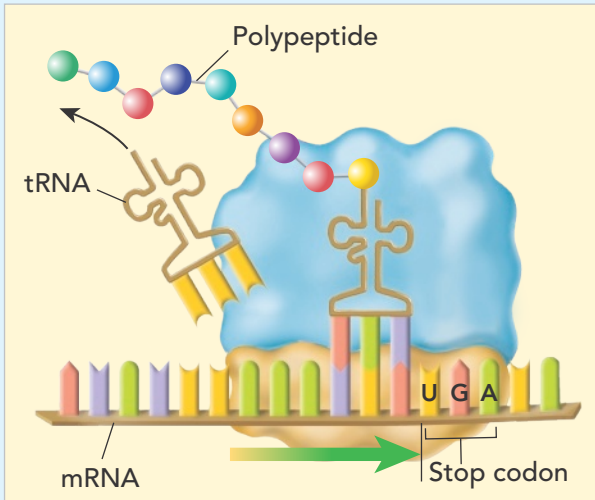
1 Translation Begins
Translation begins at AUG, the start codon. Each transfer RNA has an anticodon whose bases are complementary to the bases of a codon on the mRNA strand.



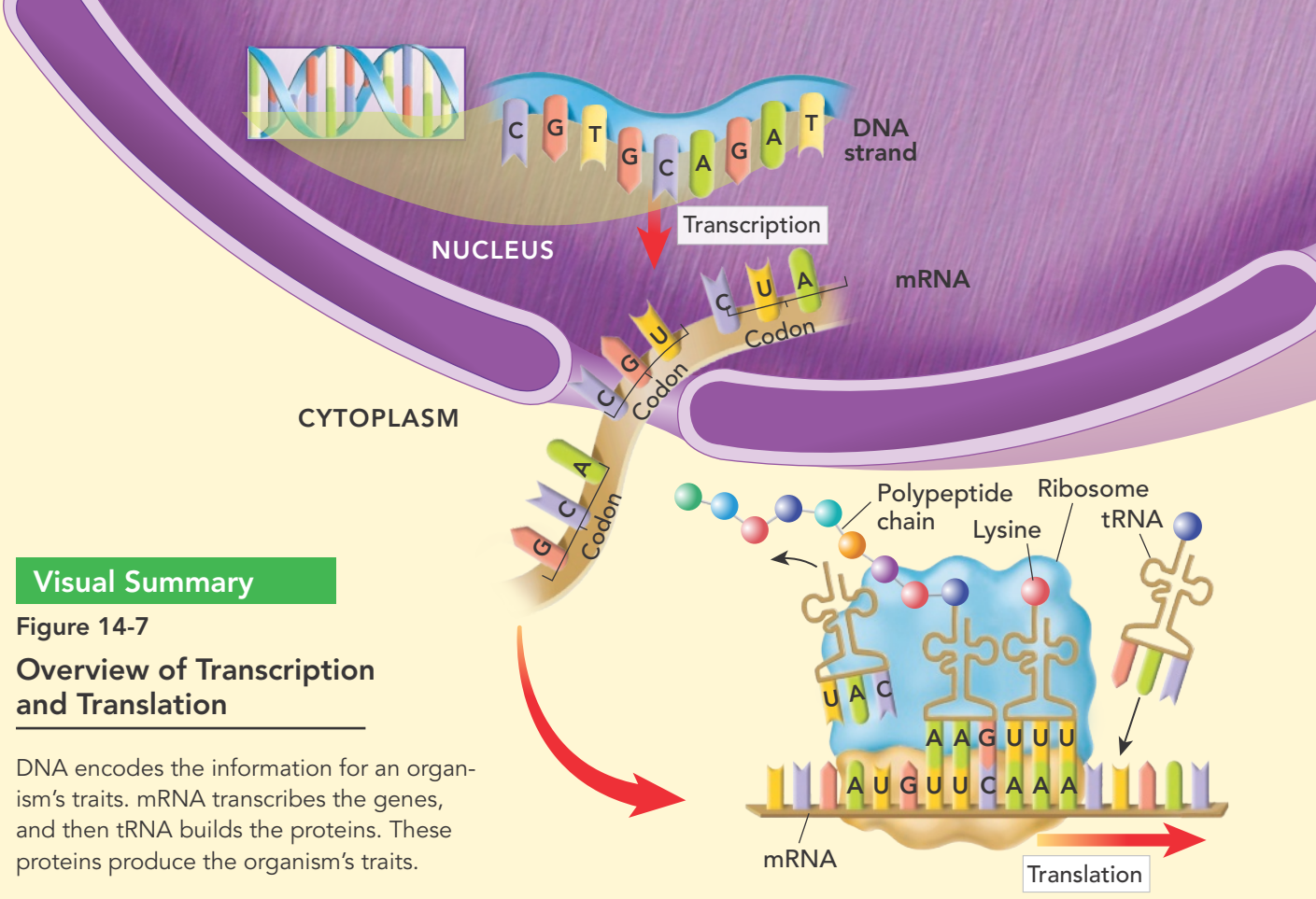
2 Transfer RNA
The ribosome positions the start codon to attract its anticodon, which is part of the tRNA that binds methionine. The ribosome also binds the next codon and its anticodon.



3 The Polypeptide "Assembly Line"
The ribosome joins the two amino acids—methionine and phenylalanine—and breaks the bond between methionine and its tRNA. The tRNA floats away from the ribosome, allowing the ribosome to bind another tRNA. The ribosome moves along the mRNA, binding new tRNA molecules and amino acids.



4 Completing the Polypeptide
The process continues until the ribosome reaches one of the three stop codons. Once the polypeptide is complete, it and the mRNA are released from the ribosome.



Visual Summary

Figure 14-7

Overview of Transcription and Translation

DNA encodes the information for an organism's traits. mRNA transcribes the genes, and then tRNA builds the proteins. These proteins produce the organism's traits.

Look at **Figure 14-6**. Like an assembly line worker who attaches one part to another, the ribosome helps form a covalent bond, called a peptide bond between the first and second amino acids. In this example, they are methionine and phenylalanine. At the same time, the bond holding the first tRNA molecule to its amino acid is broken. That tRNA then moves into a third site, from which it exits the ribosome. The ribosome then moves to the next codon, where tRNA brings in another amino acid.

The polypeptide chain continues to grow until the ribosome reaches a "stop" codon on the mRNA molecule. Then it releases both the newly synthesized polypeptide and the mRNA molecule.

READING TOOL

Use **Figure 14-7** to explain the relationship among mRNA, tRNA, and ribosomes.

The Roles of tRNA and rRNA in Translation The three major forms of RNA—mRNA, tRNA, and rRNA—are each involved in the process of translation. The mRNA molecule carries the coded message that directs the process. tRNA molecules deliver the amino acids, enabling the ribosome to "read" the mRNA's message and to get translation just right. Ribosomes themselves are composed of roughly 80 proteins and three or four different rRNA molecules. These rRNA molecules hold ribosomal proteins in place and carry out the chemical reactions that join amino acids together. As you can see in **Figure 14-7**, RNA molecules not only carry the genetic code, they also play a key role in translating it.

READING CHECK **Summarize** How do the three types of RNA work together at a ribosome to synthesize a polypeptide?

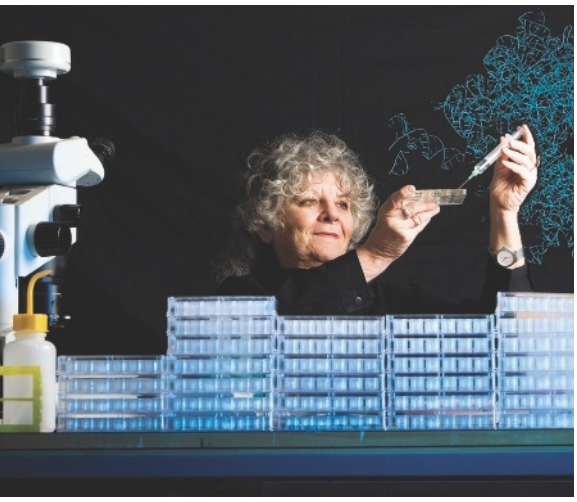


Figure 14-8

Ada Yonath

In 2009, Ada Yonath was awarded the Nobel Prize in Chemistry for mapping the structure of ribosomes.

Molecular Genetics

Gregor Mendel might have been surprised to learn that most genes contain nothing more than instructions for assembling proteins. He might have asked what proteins could possibly have to do with the color of a flower, the shape of a leaf, or the gender of a newborn baby. The answer is that proteins have everything to do with these traits. Remember that many proteins are enzymes, which catalyze and regulate chemical reactions. A gene that codes for an enzyme to produce pigment can control the color of a flower. Another gene produces proteins that regulate patterns of tissue growth in a leaf. Yet another may trigger the female or male pattern of development in an embryo. In short, proteins are microscopic tools, each specifically designed to build or operate a component of a living cell.

After scientists learned that genes were made of DNA, a series of other discoveries soon followed. When they explained the genetic code, a new scientific field called molecular biology had been established. Molecular biologists seek to understand living organisms by studying them at the molecular level, using molecules like DNA and RNA. ***Molecular biology provides a way to understand the links between genes and the characteristics they influence.*** Scientists such as Ada Yonath, shown in **Figure 14-8**, continue to make advancements in this field.

One of the most interesting discoveries of molecular biology is the near-universal nature of the genetic code. Although some organisms show slight variations in the amino acids assigned to particular codons, the code is always read three bases at a time, always in the same direction, and is always translated on ribosomes composed of RNA and protein. Despite their enormous diversity in form and function, living organisms display remarkable unity at life's most basic level, the molecular biology of the gene.

HS-LS1-1, HS-LS3-1

LESSON 14.2 Review

KEY QUESTIONS

1. How does the cell interpret the genetic code?
2. How do ribosomes use mRNA and tRNA to assemble proteins?
3. How are proteins and genes related?

CRITICAL THINKING

4. **Synthesize Information** Why can the same tRNA and rRNA molecules be used to synthesize a wide variety of polypeptides?
5. **Infer** How does the genetic code show a shared history among all organisms?
6. **Construct an Explanation** How do proteins determine the traits of an organism?

Gene Regulation and Expression

LESSON 14.3

KEY QUESTIONS

- *How are prokaryotic genes regulated?*
- *How are genes regulated in eukaryotic cells?*
- *What controls the development of cells and tissues in multicellular organisms?*

HS-LS3-1: Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring.

Think of a library filled with how-to books. Would you ever need to consult all of these books at the same time? Of course not. If you wanted to know how to fix a leaky faucet, you'd open the book about plumbing but not the one on carpentry. Now picture a bacterium such as *E. coli* with a genetic library of more than 4000 genes. How does it pick exactly the right gene to put into action?

Prokaryotic Gene Regulation

To conserve energy and resources, cells control which genes they express. For example, it would be wasteful for a bacterium to produce the enzymes to make a molecule it could get from its environment instead. By regulating gene expression, bacteria can respond to changes in their environment, such as the presence or absence of nutrients. How do they do this? ***DNA-binding proteins in prokaryotes regulate genes by controlling transcription.*** Some of these regulatory proteins switch genes on, while others turn genes off.

How does an organism know when to turn a gene on or off? *E. coli*, shown in **Figure 14-9**, provides us with a clear example. A total of 4288 genes code for proteins in *E. coli*. Among them is a cluster of 3 genes that must be turned on together before the bacterium can break apart lactose, a type of sugar. Lactose provides food for the bacterium. Because the three genes are "operated" together, the three lactose genes in *E. coli* are called the *lac* operon. An **operon** is a group of genes that are regulated together.

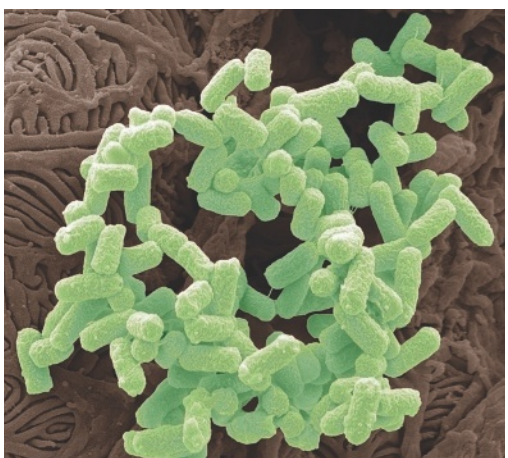


Figure 14-9
Escherichia coli

Even "simple" organisms like *E. coli* have thousands of genes to regulate (false-colored SEM 3600x).

VOCABULARY

operon
operator
differentiation
homeotic gene
homeobox gene
Hox gene

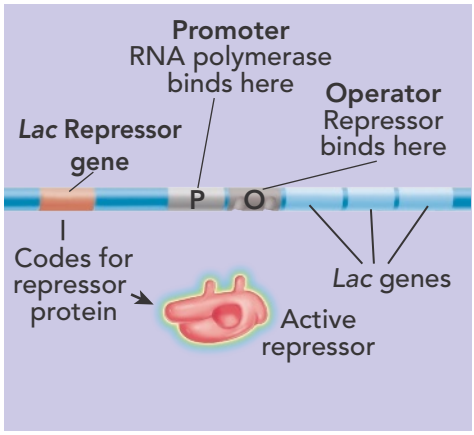
READING TOOL

Identify the main ideas and details for each heading in this lesson. Record your observations in the table in your **Biology Foundations Workbook.**

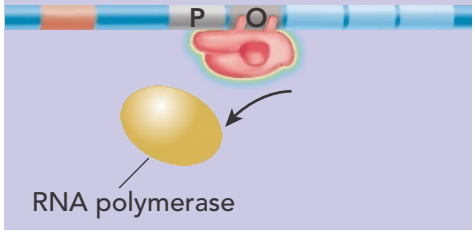
Figure 14-10

Gene Regulation in Prokaryotes

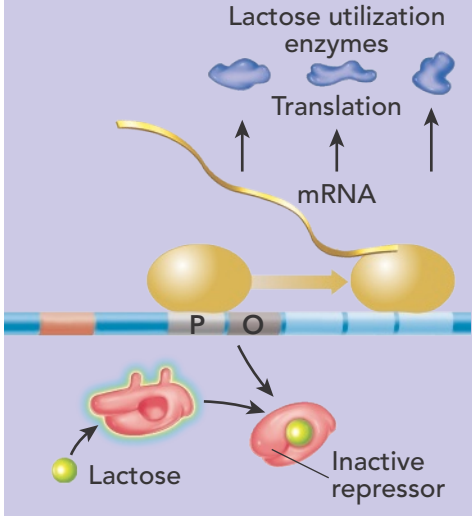
The *lac* genes in *E. coli* are turned off by *lac* repressors and turned on in the presence of lactose.



When lactose is not present, the repressor protein binds to the operating region. This blocks RNA polymerase from transcribing the *lac* genes.



When lactose is present, it binds to the repressor. This causes the release of the repressor, which then moves away from the operating region. Transcription can now take place.



The *Lac* Operon

Why must *E. coli* be able to switch the *lac* genes on and off? Lactose is a compound made up of two sugars: galactose and glucose. To use lactose for food, the bacterium must transport lactose across its cell membrane and then break the bond between glucose and galactose. These tasks are performed by proteins coded for by the genes of the *lac* operon.

Remarkably, the bacterium almost seems to "know" when the products of the *lac* operon genes are needed, and when they're not needed. For example, if the bacterium grows in a medium where lactose is the only food source, the genes must be transcribed to produce the proteins. However, if the environment changes to another food source, such as glucose, then the genes are not transcribed. How does the cell turn the expression of these genes on and off, and in such a useful way?

Promoters and Operators

The secret to the control of the *lac* operon lies on one side of the operon's three genes, where there are two regulatory regions. The first is a promoter (P), which is a site where RNA polymerase can bind to begin transcription. The other region is called the **operator** (O). The O site is where a DNA-binding protein known as the *lac* repressor can bind to DNA.

The Lac Repressor Blocks Transcription

When lactose is not present, the *lac* repressor binds to the O region and RNA polymerase cannot reach the *lac* genes to begin transcription, as shown in **Figure 14-10**. In effect, the binding of the repressor protein switches the operon "off" by preventing the transcription of its genes.

Lactose Turns the Operon "On"

Besides its DNA binding site, the *lac* repressor protein has a binding site for lactose itself. When lactose is in the medium, some of it diffuses into the cell and attaches to the *lac* repressor. This changes the shape of the repressor protein in a way that causes it to fall off the operator. Now, with the repressor no longer bound to the O site, RNA polymerase can bind to the promoter and transcribe the genes of the operon. As a result, in the presence of lactose, the operon is automatically switched on. Messenger RNA transcribed from the *lac* genes is then translated into proteins that enable lactose to cross the cell membrane and to be broken down for use as an energy source by the cell. Many other prokaryotic genes are switched on or off by similar mechanisms.

READING CHECK Review What is the function of the operator in the *lac* operon?

Eukaryotic Gene Regulation

The general principles of gene expression in prokaryotes also apply to eukaryotes, although the regulation of many eukaryotic genes is much more complex. **Figure 14-11** shows several features of a typical eukaryotic gene. One of these is the TATA box, a short region of DNA, about 25 or 30 base pairs before the start of a gene, containing the sequence TATATA or TATAAA. The TATA box binds a protein that helps position RNA polymerase by marking a point just before the beginning of a gene.

Transcription Factors DNA-binding proteins known as transcription factors play an important part in regulating gene expression. Some transcription factors open up tightly packed chromatin to help attract RNA polymerase. Others block access to certain genes, much like prokaryotic repressor proteins. Sometimes multiple factors must bind to DNA sequences known as enhancers before a gene can be transcribed. ***By binding DNA sequences in the regulatory regions of eukaryotic genes, transcription factors control gene expression.***

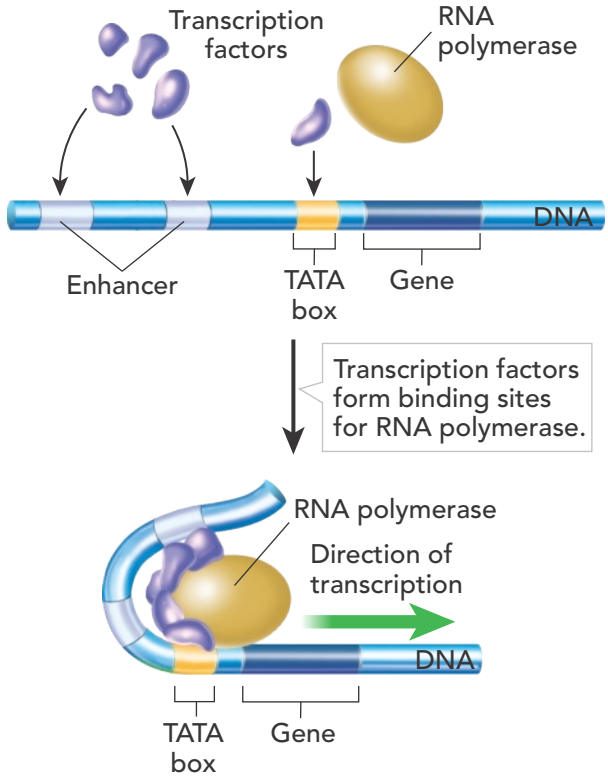
A transcription factor can activate scores of genes at once, thereby dramatically affecting patterns of gene expression. Steroid hormones, for example, are chemical messengers that enter cells and bind to receptor proteins. These hormone–receptor complexes then act as transcription factors that bind to DNA and activate multiple genes. Eukaryotic gene expression can also be regulated by many other factors, including the exit of mRNA molecules from the nucleus, the stability of mRNA, and even the breakdown of a gene's protein products.

Cell Specialization Why is gene regulation in eukaryotes more complex than in prokaryotes? Think about the way in which genes are expressed in a multicellular organism. The genes that code for liver enzymes, for example, are not expressed in nerve cells. Keratin, an important protein in skin cells, is not produced in blood cells. Cell differentiation requires genetic specialization, yet most of the cells in a multicellular organism carry the same DNA in their nucleus. Complex gene regulation in eukaryotes makes it possible for cells to be differentiated and specialized. Gene regulation also allows multicellular organisms to reproduce. A new organism generally begins as a single cell. Complex changes in gene expression allow the cell to develop into a functioning multicelluar organism.

Figure 14-11

Eukaryotic Gene Regulation

Many eukaryotic genes include a region called the TATA box that helps position RNA polymerase.



READING TOOL

Construct a flowchart to show how transcription factors affect gene regulation in eukaryotes.

INTERACTIVITY

Investigate prokaryotic and eukaryotic gene regulation.

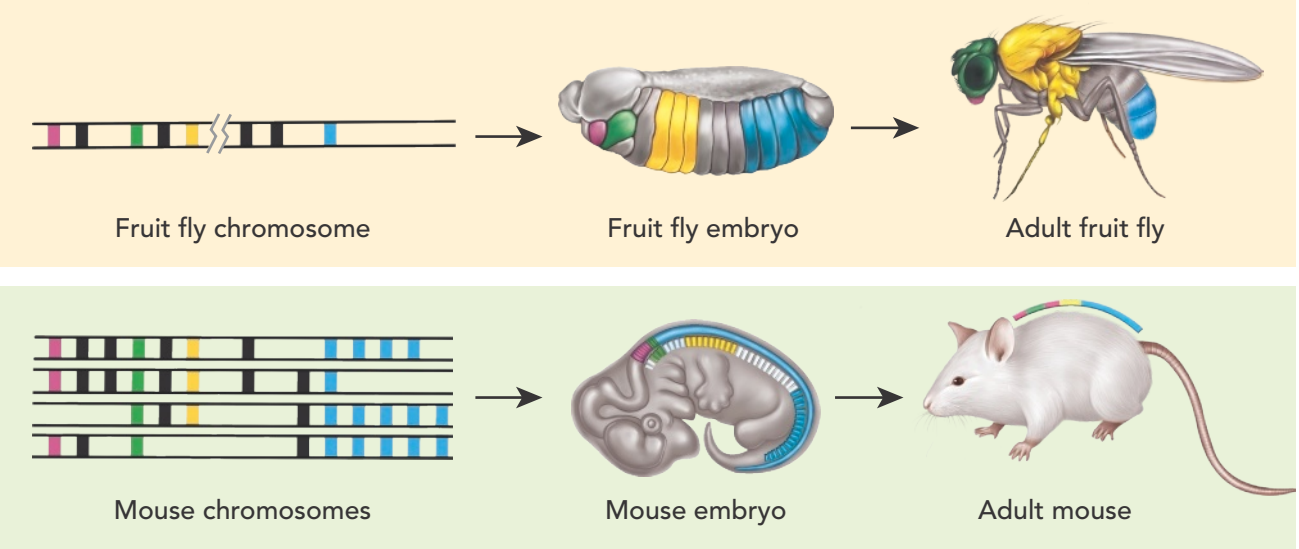


Figure 14-12

Hox Genes and Body Development

In fruit flies, a series of Hox genes along a chromosome determine the basic body structure. Mice have similar genes on four different chromosomes. The colored areas on the fly and mouse show the approximate body areas affected by genes of the corresponding colors. **Interpret Visuals** What section of the bodies of flies and mice is coded by the genes shown in blue?

BUILD VOCABULARY

Word Origins The word part *homeo* comes from the Latin and Greek part *homio*, meaning "similar to" or "the same kind." Homeobox genes are a group of similar genes that regulate specific structures.

Genetic Control of Development

Regulating gene expression is especially important during the earliest stages of development. The activation of genes in different parts of an embryo cause cells to differentiate. The process of **differentiation** gives rise to specialized tissues and organs.

Homeotic Genes American biologist Edward B. Lewis was the first to show that a specific group of genes controls the identities of body parts in the embryo of the common fruit fly. Change one of these genes, and a body part like an antenna might actually be changed into a leg. From Lewis's work it became clear that a set of master control genes, known as **homeotic genes**, regulates organs that develop in specific parts of the body.

Molecular studies of homeotic genes show that they share a very similar 180-base DNA sequence, which was given the name *homeobox*. **Homeobox genes** code for transcription factors that activate other genes that are important in cell development and differentiation. In flies, a group of homeobox genes known as **Hox genes** are located side by side in a single cluster. As shown in **Figure 14-12**, Hox genes determine the identities of each segment of a fly's body. They are arranged in the exact order in which they are expressed, from anterior to posterior. A mutation in one of these genes can completely change the organs that develop in specific parts of the body.

Remarkably, clusters of Hox genes exist in the DNA of other animals, including humans. These genes are arranged in the same way—from head to tail. The function of Hox genes in humans seems to be almost the same as it is in fruit flies: They tell the cells of the body how to differentiate as the body grows. This means that nearly all animals, from flies to mammals, share the same basic tools for building the different parts of the body.

Common patterns of genetic control exist because all these genes have descended from the genes of common ancestors. ***Master control genes are like switches that trigger particular patterns of development and differentiation in cells and tissues.*** The details can vary from one organism to another, but the switches are nearly identical. Recent studies have shown that the very same Hox gene that triggers the development of hands and feet is also active in the fins of certain fish.

INTERACTIVITY

Investigate the science behind the genetically modified mosquito being developed to fight Zika in the United States.

Epigenetics Cells have another way to regulate gene expression. Recall that nuclear DNA is coiled around protein clusters, called nucleosomes, to form chromatin. In places where chromatin is tightly packed, transcription factors cannot access their DNA binding sites, and gene expression is blocked. By contrast, in regions where chromatin is opened up, gene expression is enhanced, as shown in **Figure 14-13**.

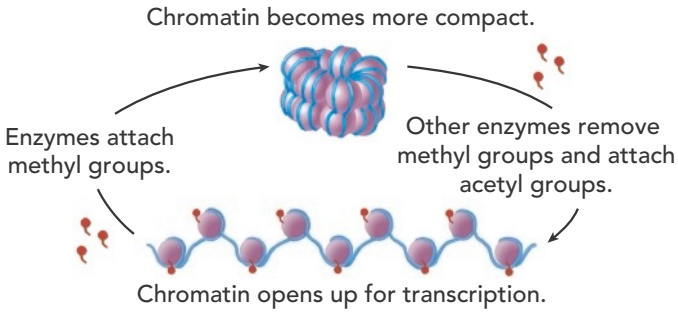


Figure 14-13
Effect of Chemical Marks

The presence or absence of chemical marks determines how compact chromatin is in a given region of DNA. For transcription to occur, the chromatin must be less compact.

Cells can regulate the state of chromatin by enzymes that attach chemical groups to DNA and to histone proteins. Specifically, the attachment of large numbers of methyl groups (—CH_3) will cause chromatin to condense, shutting down gene expression. Conversely, the attachment of acetyl groups (—CO-CH_3) will open chromatin up for transcription and gene expression.

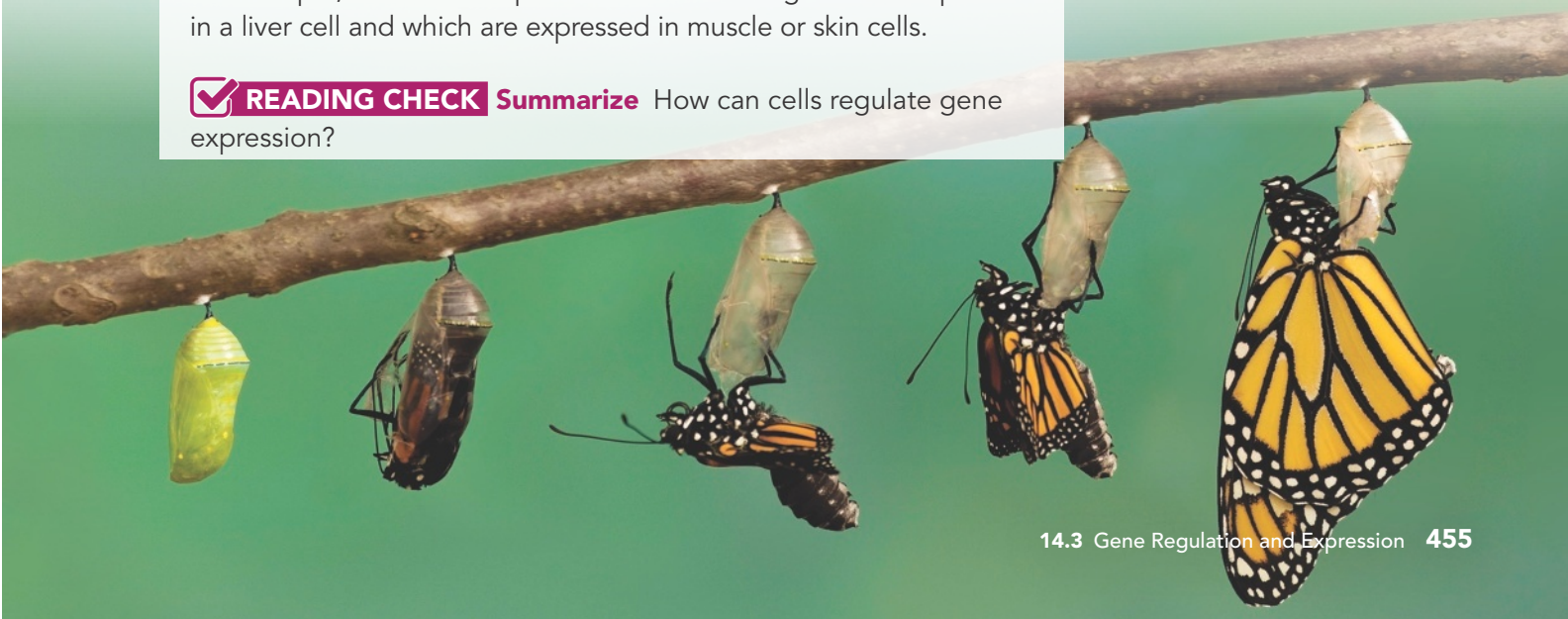
These chemical marks on chromatin are said to be epigenetic, meaning they are above the level of the genome. Epigenetic marks do not change DNA base sequences. Instead, they influence patterns of gene expression over long periods of time. During development, for example, the marks help to determine which genes are expressed in a liver cell and which are expressed in muscle or skin cells.

READING CHECK **Summarize** How can cells regulate gene expression?

CASE STUDY

Figure 14-14
Epigenetics

A caterpillar, pupa, and butterfly all have exactly the same genes. Epigenetic mechanisms control which genes are on and which are off during each stage of the insect's life cycle.



INTERACTIVITY

Figure 14-15

Environmental Influences on Gene Expression

The coloring of the coat of a Himalayan rabbit is one example of the effect of the environment on gene expression. **Predict** What would happen if a cold pack were strapped to a Himalayan rabbit's back while its fur was growing in?

Raised at temperatures below 25°C

Raised at temperatures above 30°C

Environmental Influences As you have seen, cell differentiation is controlled at least in part by the regulation of gene expression. Conditions in an organism's environment play a role too. In prokaryotes and eukaryotes, environmental factors such as temperature, salinity, and nutrient availability can regulate gene expression. For example, the *lac* operon in *E. coli* is switched on only when lactose is the sole food source in the bacteria's environment.

The environment can often influence how and when epigenetic marks are attached to chromatin. One well-known example involves Dutch children born near the end of World War II. When these children reached adulthood, they had much higher rates of obesity, diabetes, and cardiovascular disease than their parents and ancestors. Why? Because epigenetic marks had been attached to these individuals' DNA as they developed inside their malnourished mothers. Insufficient nourishment during the first three months of development changed the way genes were expressed in the growing fetus. As a result of these epigenetic changes, the body was altered so that it was better suited for an environment where food was scarce. However, life gradually returned to normal after the war, and food because plentiful again. This had a profoundly negative, lifelong impact on individuals whose gene expression was epigenetically altered to cope with food shortages.

Environmental factors can also directly affect the expression of other genes. A dramatic example involves Himalayan rabbits carrying a particular gene for fur color. In a rabbit raised at temperatures between 15°C and 25°C, the gene produces black color in the fur on the animal's nose, ears, and on the tips of its feet, as shown in **Figure 14-15**. The gene is not fully active at temperatures above 30°C, so only the coldest portions of the rabbit's body allow the gene to function. If a rabbit is raised at temperatures above 30°C, the gene is completely inactive, and the entire rabbit is white.

HS-LS3-1

LESSON 14.3 Review

KEY QUESTIONS

1. What controls transcription in prokaryotes?
2. What are three mechanisms by which transcription factors regulate eukaryotic gene expression?
3. Why are master control genes almost universal and common to different organisms?

CRITICAL THINKING

4. **Construct an Explanation** How does the *lac* operon help *E. coli* conserve energy and other resources?
5. **Engage in Argument** You are studying the genes of fruit flies. Your partner claims that each gene matches to a specific body part, such as the head, wings, and tail. How would you argue for or against this claim?

Mutations

LESSON 14.4

A mutation causes dwarfism in Bantam chickens.

KEY QUESTIONS

- *In what ways do mutations change genetic information?*
- *How do mutations affect genes?*

HS-LS3-1: Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring.

HS-LS3-2: Make and defend a claim based on evidence that inheritable genetic variations may result from: (1) new genetic combinations through meiosis, (2) viable errors occurring during replication, and/or (3) mutations caused by environmental factors.

As you've seen, the sequence of bases in DNA are like the letters of a coded message. But what would happen if a few of those letters changed accidentally, altering the message? Could the cell still understand its meaning? Think about what might happen if someone changed at random a few lines of code in a computer program. Would the program be affected, and in ways that you would notice?

Types of Mutations

Now and then cells make mistakes in copying their own DNA. An incorrect base is inserted or a base is skipped during transcription. These variations are called **mutations**, from the Latin word *mutare*, meaning "to change." Mutations are heritable changes in genetic information. ***Mutations can involve changes in the sequence of nucleotides in DNA or changes in the number or structure of chromosomes.***

Point Mutations Mutations that change a single base pair are known as **point mutations** because they occur at a single point in the DNA sequence. Point mutations usually involve a substitution, in which one base is changed to a different base. Substitutions usually affect no more than a single amino acid, and sometimes have no effect at all. For example, if a mutation changed one codon of mRNA from CCC to CCA, the codon would still specify the amino acid proline. Mutations like this are known as *silent mutations*, since they don't affect amino acid sequence. But changing CCC to ACC might be more significant, since it would replace proline with the amino acid threonine. Mutations that change the amino acid specified by a codon are called *missense mutations*.

VOCABULARY

mutation
point mutation
frameshift mutation
mutagen
polyploidy

READING TOOL

As you read, find a brief description of each type of genetic mutation. Fill in the table in your **Biology Foundations Workbook** with the description and the possible effects.

READING TOOL

As you read about the different types of mutations in this section, create a two-column table in which you list each type of mutation and the effect it has on genetic information.

Sometimes a point mutation can have severe effects on gene expression. For example, if a mutation changed an mRNA codon from AAA to UAA, it would result in a stop codon instead of lysine. This is known as a *nonsense mutation* because it would cause translation to stop before the protein was finished. Depending on the position of the stop codon, it could result in the production of a defective protein.

Insertions and Deletions Mutations in which one or many bases are inserted or removed from the DNA sequence are called insertions and deletions. As shown in **Figure 14-16**, the significance of these changes can be dramatic. Remember that the genetic code is read three bases at a time. If a nucleotide is added or deleted, the bases are still read in groups of three, but now those groupings change in every codon that follows the mutation.

INTERACTIVITY

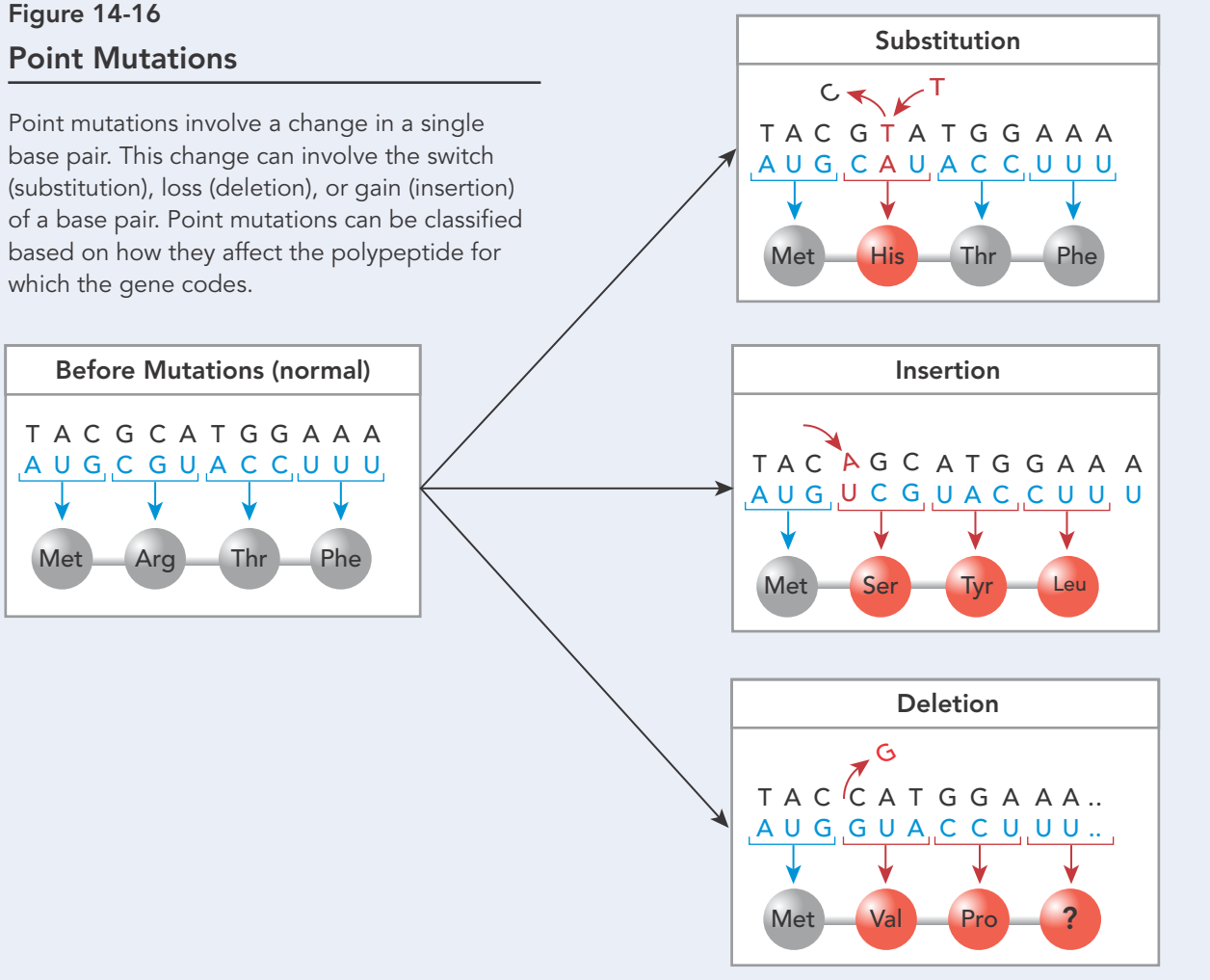
Learn about the different types of point mutations and their effects.

Insertions and deletions are also called **frameshift mutations** because they shift the "reading frame" of the genetic message. By shifting the reading frame, frameshift mutations can change every amino acid that follows the point of the mutation. They can alter a protein so much that it is unable to perform its normal functions.

Figure 14-16

Point Mutations

Point mutations involve a change in a single base pair. This change can involve the switch (substitution), loss (deletion), or gain (insertion) of a base pair. Point mutations can be classified based on how they affect the polypeptide for which the gene codes.



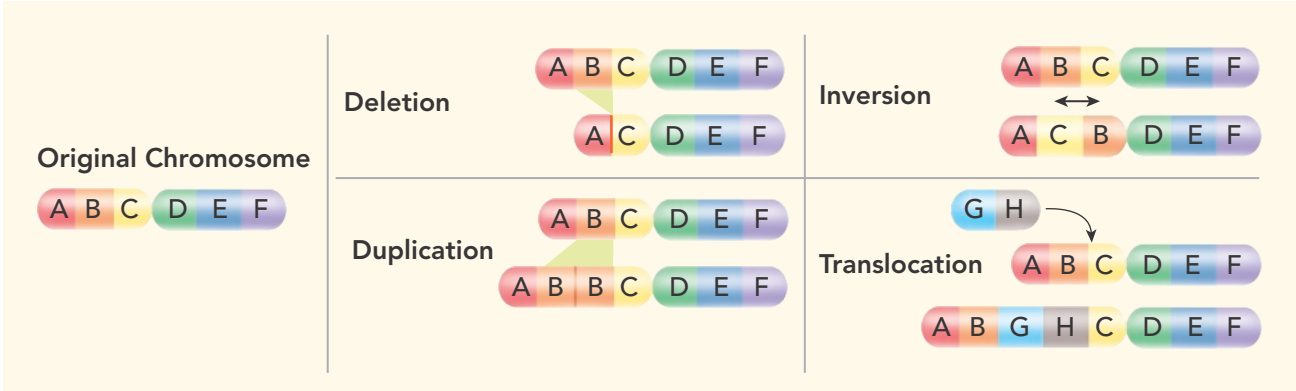


Figure 14-17

Chromosomal Mutations

Mutations that change the structure or number of chromosomes are called chromosomal mutations. **Analyze Diagrams** What is the difference between inversion and translocation?

INTERACTIVITY

Investigate different types of mutations and their effects on organisms.

Chromosomal Mutations Chromosomal mutations involve changes in the number or structure of chromosomes. These mutations can change the location of genes on chromosomes and can even change the number of copies of some genes.

There are four types of chromosomal mutations: deletion, duplication, inversion, and translocation. In **Figure 14-17**, the top chromosome in each example is the original chromosome. The chromosome underneath it is the chromosome that results from the mutation. Deletion involves the loss of all or part of a chromosome; duplication produces an extra copy of all or part of a chromosome; and inversion reverses the direction of parts of a chromosome. Translocation occurs when part of one chromosome breaks off and attaches to another.

READING CHECK **Describe** What is a frameshift mutation?

Effects of Mutations

Genetic material can be altered by natural events or by artificial means. The resulting mutations may or may not affect an organism. And some mutations that affect individual organisms can also affect a species or even an entire ecosystem.

Many mutations are produced by errors in genetic processes. For example, some point mutations are caused by errors during DNA replication. The cellular machinery that replicates DNA inserts an incorrect base roughly once in every 10 million bases. But small changes in genes can gradually accumulate over time.

HS-LS3-2

Modeling Lab

Open-ended Inquiry

The Effect of Mutations

Problem How can mutations affect a protein?

In this lab, you will be exploring different types of mutations and the possible effects they can have on a protein.

You can find this lab in your digital course.

ANIMATION

hhmi | BioInteractive

Figure 14-18

Damage to DNA leads to mutation

The ultraviolet light in sunlight can cause mutations in skin cells, resulting in skin cancer. Sunscreen and protective clothing help shield beachgoers from harmful UV radiation.

BUILD VOCABULARY

Root Words The root word *gen* means "producing." A **mutagen** is something that produces a mutation.

VIRTUAL LAB

Identify which type of mutation can lead to a white-eyed fruit fly.

Mutagens Some mutations arise from **mutagens**, chemical or physical agents in the environment. Chemical mutagens include certain pesticides, a few natural plant alkaloids, tobacco smoke, and environmental pollutants. Physical mutagens include some forms of electromagnetic radiation, such as ultraviolet light, shown in **Figure 14-18**, and X-rays. If these agents interact with DNA, they can produce mutations at high rates. Cells can sometimes repair the damage; but when they cannot, the DNA base sequence changes permanently. Some compounds interfere with base-pairing, increasing the error rate of DNA replication. Other mutagens weaken the DNA strand, causing breaks and inversions that produce chromosomal mutations.

Harmful and Helpful Mutations As you've already seen, some mutations don't even change the amino acid specified by a codon, while others may significantly alter a complete protein or even an entire chromosome. ***The effects of mutations on genes vary widely. Some have little or no effect, some produce beneficial variations, and some negatively disrupt gene function.*** Many if not most mutations are neutral; they have little or no effect on the expression of genes or the function of the proteins for which they code. Whether a mutation is negative or beneficial depends on how its DNA changes relative to the organism's situation. Mutations are often thought of as negative, since they can disrupt the normal function of genes. However, without mutations, organisms could not evolve. Mutations are the source of genetic variability in a species.

Harmful Effects Some of the most harmful mutations are those that dramatically change protein structure or gene activity. The defective proteins produced by these mutations can disrupt normal biological activities, and result in genetic disorders. Some cancers, for example, are the product of mutations that cause the uncontrolled growth of cells. A human genetic disorder called xeroderma pigmentosum is the result of a mutation that inactivates a protein that normally repairs DNA damaged by ultraviolet (UV) light. Individuals with this mutation have to avoid sunlight as much as possible because their skin cells can become cancerous as a result of UV damage to DNA.

Figure 14-19

Effects of Mutations

Polyploidy is a condition that is generally lethal in animals. But in plants, like these limes (left), polyploidy often produces stronger plants and larger fruits. A mutation damaged the immune system of the nude mouse (bottom), making it valuable for scientific research.

Helpful Effects Some of the variation produced by mutations can be highly advantageous to an organism or species. ***Mutations often produce proteins with new or altered functions that can be useful to organisms in different or changing environments.*** For example, over the past 20 years, mutations in the mosquito genome have made many African mosquitoes resistant to the chemical pesticides once used to control them. This may be bad news for humans, but it is highly beneficial to the insects themselves. Beneficial mutations occur in humans, too, including ones that increase bone strength and density, making fractures less likely. Some mutations increase resistance to HIV, the virus that causes AIDS.

Plant and animal breeders often make use of "good" mutations. For example, when a complete set of chromosomes fails to separate during meiosis, the gametes that result may produce triploid (3N) or tetraploid (4N) organisms. The condition in which an organism has extra sets of chromosomes is called **polyploidy**. Polyploid plants, like the one shown in **Figure 14-19,** are often larger and stronger than diploid plants. Important crop plants—including bananas, limes, and strawberries—have been produced this way. Polyploidy also occurs naturally in citrus plants, often through spontaneous mutations.

HS-LS3-1, HS-LS3-2

LESSON 14.4 Review

KEY QUESTIONS

1. Describe the ways mutations can affect DNA and chromosomes.
2. What are the possible ways that a mutation may affect an organism?

CRITICAL THINKING

3. **Construct Explanations** The effects of a mutation are not always visible. Choose a species and explain how you would determine whether a mutation has occurred. How might you determine what type of mutation it is?
4. **Evaluate Claims** A science student claims that a substitution mutation is less likely to affect gene function than an insertion or deletion mutation. Use logical reasoning to evaluate this claim.
5. **Synthesize Information** What are three possible ways that a mutation could change DNA, yet have no measurable effect on the organism?
6. **Construct an Explanation** After many years of normal function, a cell begins producing different proteins than it produced before. Propose two different explanations for this change.

CASE STUDY WRAP-UP

How does a plant remember winter?

The environment can exert long-term influences on gene expression by triggering epigenetic changes in DNA. Flowering in winter wheat is regulated by just such changes.

HS-ETS1-1, HS-LS3-3

Make Your Case

As you have learned, genes are expressed through the processes of transcription and translation. But that's just one part of the story. Not all genes are expressed all the time. The study of epigenetics involves the many mechanisms that affect when and how genes are expressed. Some of these mechanisms alter the structure of DNA, while others change the histones that hold DNA in place. Even a simple change to DNA can have far-reaching consequences to the organism.

Obtain Information

1. **Ask Questions** Starting with winter wheat as an example, research the role of epigenetic changes in other organisms. Use the "agouti mutation" in mice as a specific example.
2. **Conduct Research** Research winter wheat, vernalization, and epigenetics. Then identify a social or technological problem that epigenetics might help solve. Evaluate your sources for reliability.

Cancer cells (yellow)
(SEM 2400x)

Technology on the Case

Epigenetics and Cancer

What causes cancer? For many years, scientists thought that the main cause was damage to DNA. Chemicals in tobacco cause this type of damage, which is why tobacco users have a high risk for cancer. However, new research shows that epigenetic mechanisms can also play a role in causing cancer. For example, some genes act to regulate the growth of the cell. If an epigenetic change "turns off" these genes, then cell growth will keep going unchecked and lead to a cancerous tumor. Another example involves the genes that help repair DNA. If these genes become deactivated, then cancer could be the result.

The good news is that epigenetic changes sometimes can be reversed. Researchers are investigating several epigenetic treatments for cancer, and the results have been encouraging. The goal of epigenetic therapy is not to kill the cancer cells, which is the goal of conventional treatments for cancer. Instead, epigenetic therapy works by reactivating the genes that help the body fight cancer naturally.

Scientists are also applying epigenetics to help explain some cancer statistics. For example, research shows that people who regularly take aspirin are less likely to get certain types of cancer. The reason might be that aspirin reduces inflammation within cells. If the inflammation affects DNA in the cell nucleus, then epigenetic changes could be the result.

Careers on the Case

Work Toward a Solution

The study of epigenetics is being applied in some unexpected ways, such as nutrition.

Nutritionist

To help people eat healthful diets, nutritionists study the nutrients in foods and the way they affect the body. Nutritionists may work in hospitals or doctor's offices, or work for companies that manufacture foods.

VIDEO

Watch this video to learn about other careers in biology.

Lesson Review

Go to your Biology Foundations Workbook for longer versions of these lesson summaries.

14.1 RNA

Unlike DNA, RNA uses the sugar ribose instead of deoxyribose, RNA is generally single stranded, and RNA contains uracil in place of thymine. There are three main types of RNA: messenger RNA (mRNA), ribosomal RNA (rRNA), and transfer RNA (tRNA).

In transcription, segments of DNA serve as templates to produce complementary RNA molecules.

- RNA
- messenger RNA
- ribosomal RNA
- transfer RNA
- transcription
- RNA polymerase
- promoter
- intron
- exon

RNA
Ribonucleic Acid

DNA
Deoxyribonucleic Acid

Compare and Contrast What are the differences between RNA and DNA?

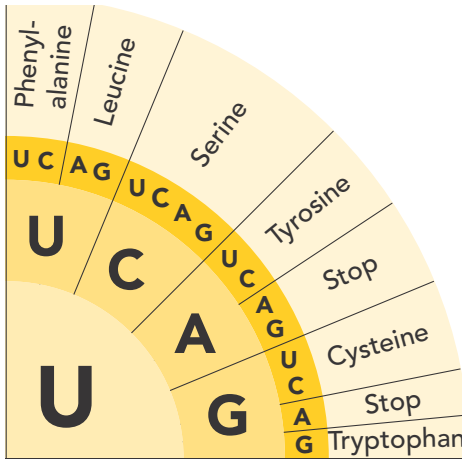
14.2 Ribosomes and Protein Synthesis

The genetic code is a language composed of the four different bases of RNA: adenine, cytosine, guanine, and uracil. The code is read three letters at a time to carry instructions for the 20 different amino acids commonly found in polypeptides. Each three-letter combination in mRNA is a codon. Because there are four different bases, there are 64 possible three-base codons in the genetic code.

The order in which amino acids are joined together in a peptide determines the shape, the chemical properties, and ultimately the function of the protein. In the cell, ribosomes use the sequence of codons in mRNA to assemble amino acids into polypeptide chains in a process called translation. All three major forms of RNA are involved in the process of translation.

After the genetic code was discovered, the new field of molecular biology was established. Molecular biologists seek to understand the links between genes and the characteristics they influence.

- polypeptide
- genetic code
- codon
- translation
- anticodon



Interpret Diagrams Which amino acid is specified by the codon UAC?

14.3 Gene Regulation and Expression

DNA-binding proteins in prokaryotes regulate genes by controlling transcription.

By binding DNA sequences in the regulatory regions of eukaryotic genes, transcription factors control gene expression.

Master control genes are like switches that trigger particular patterns of development and differentiation in cells and tissues.

- operon
- operator
- differentiation
- homeotic gene
- homeobox gene
- Hox gene

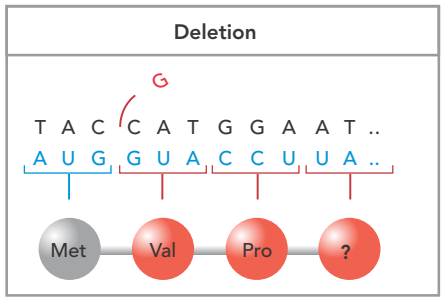
Apply Concepts What is a genetic explanation for the difference in these two Himalayan rabbits?

14.4 Mutations

Mutations can involve changes in the sequence of nucleotides in DNA. They can also involve changes in the number or structure of chromosomes in an organism. A change in a single base pair is known as a point mutation. The insertion or deletion of one or many bases in DNA is called a frameshift mutation. These mutations shift the "reading frame" of the genetic message. Chromosomal mutations involve changes in the number or structure of chromosomes and include deletion, duplication, inversion, and translocation.

Some mutations arise from mutagens, which interact with DNA to produce cell damage. The most harmful mutations dramatically change protein structure or gene activity, producing genetic disorders, such as cancer.

- mutation
- point mutation
- frameshift mutation
- mutagen
- polyploidy



Cause and Effect How does the deletion of a single base cause a frameshift mutation?

Organize Information

Complete the table to describe the molecules involved in protein synthesis. One entry is completed for you.

Molecule	Function
mRNA	1.
rRNA	2.
tRNA	Binds amino acids, brings them to the ribosomes, and reads the mRNA codons by base pairing
Introns and exons	3.
Transcription factors	4.

PERFORMANCE-BASED ASSESSMENT

A New Kind of Drug: mRNA

Evaluate a Solution

HS-LS1-1, HS-LS3-1, HS-ETS1-3

STEM What happens when you take a conventional drug, such as aspirin or penicillin? The drug travels through the blood stream, and then is absorbed by body cells or (as with penicillin) by the cells of bacteria or other invaders. The drug does its work, but eventually it goes away. Enzymes and other mechanisms break apart drugs and remove them from the body.

Today, researchers are trying to develop drugs in a very different way. The new drugs are a modified form of messenger RNA (mRNA). Instead of directly completing the tasks of the drug, the modified mRNA enters the cell and directs protein synthesis. Then the protein takes action as a drug or medicine. The protein might be a vaccine or antibody, or it might be an enzyme that the body cannot make or that it needs in an increased supply.

To develop mRNA drugs, researchers had to find a way to make the molecules last longer in the body than they generally do. They also needed to "trick" the target cell into recognizing and accepting the drug. Otherwise, the cell might attack the drug as if it were a virus.

Researchers met both challenges with the same solution. The drug is not quite the same as the natural mRNA found in cells. Instead, it uses a few nucleotides that are slightly different from the normal nucleotides found in RNA. The modifications make the mRNA both more stable and less viruslike.

The process of RNA therapy can be summarized as follows:

1. Modified mRNA is synthesized in a laboratory cell culture.
2. The mRNA is delivered into the patient. Often it is injected with a vector, or carrier, such as a deactivated virus.
3. Inside cells, the mRNA attaches to ribosomes, as if it were the natural mRNA of the cell.
4. The mRNA directs protein synthesis.
5. The protein fills a positive role in the body, just like a conventional drug or medicine.

SCIENCE PROJECT

1. **Form a Hypothesis** Would this therapy work if mRNA were replaced with other types of RNA, such as ribosomal RNA (rRNA) or transfer RNA (tRNA)? Use evidence to support your hypothesis.
2. **Evaluate a Solution** What are the advantages of using mRNA, rather than DNA, for directing the synthesis of the drug? (**HINT:** Remember the role of regulating gene expression in the cell.)
3. **Develop Models** Review the steps of administering an mRNA drug. Add illustrations to the figure to model the processes that are occuring inside the cell with the mRNA drug. Either draw the illustrations by hand or copy diagrams from the chapter.
4. **Use Models** Use your model to compare the administration of an mRNA drug to the protein synthesis that the cell normally performs.
5. **Conduct Research** Use an online search engine to research more information about mRNA drugs, their uses, and their development. Be sure to take notes and to cite your sources.
6. **Communicate Information** Share your findings about mRNA drugs in an oral report to the class, or in a written essay or computer presentation. Address these questions:
   - Why are companies investing in mRNA drugs?
   - What advances in technology have allowed mRNA drugs to be developed?
   - What kinds of proteins can mRNA drugs be used to synthesize?

ASSESSMENT

KEY QUESTIONS AND TERMS

14.1 RNA

HS-LS1-1, HS-LS3-1

1. RNA differs from DNA in that RNA has
   a. a double strand and contains uracil.
   b. a single strand and contains adenine.
   c. a double strand and contains thymine.
   d. a single strand and contains uracil.
2. From which molecules are mRNA molecules transcribed?
   a. tRNA **c**. DNA
   b. rRNA **d**. protein
3. Which of the following are found in both DNA and RNA?
   a. ribose, phosphate groups, and adenine
   b. deoxyribose, phosphate groups, and guanine
   c. phosphate groups, guanine, and cytosine
   d. phosphate groups, guanine, and thymine
4. What is the function of RNA polymerase in the process of transcription?
5. Identify the three types of RNA and describe their functions.
6. What are introns and exons?

14.2 Ribosomes and Protein Synthesis

HS-LS1-1, HS-LS3-1

7. What happens during translation?
   a. Messenger RNA is made from a DNA code.
   b. The cell uses a messenger RNA code to make proteins.
   c. Transfer RNA is made from a messenger RNA code.
   d. Copies of DNA molecules are made.
8. The genetic code is always read
   a. 3 bases at a time in the same direction.
   b. 4 bases at a time in the same direction.
   c. 3 bases at a time and the direction varies.
   d. 4 bases at a time and the direction varies.
9. Ribosomes are tiny "factories" within cells that do all of the following EXCEPT
   a. decode an mRNA message into a protein.
   b. assemble amino acids into polypeptide chains.
   c. attach to mRNA molecules in the cytoplasm.
   d. translate DNA into RNA.
10. What are the four bases of the genetic code?
11. What is the difference between translation and transcription?
12. How is molecular biology related to genetics?

14.3 Gene Regulation and Expression

HS-LS3-1

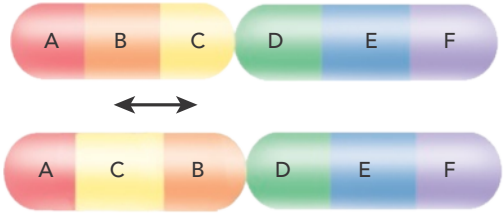
13. Gene regulation in eukaryotic cells
    a. usually involves operons.
    b. is simpler than in prokaryotes.
    c. allows for cell specialization.
    d. includes the action of an operator region.
14. What is a promoter?
    a. a binding site for DNA polymerase
    b. a binding site for RNA polymerase
    c. a start signal for replication
    d. a stop signal for transcription
15. What happens to *lac* repressors in *E. coli* when lactose is present?
16. Explain the function of homeotic genes and Hox genes.
17. Describe how a TATA box helps position RNA polymerase in a eukaryotic cell.

14.4 Mutations

HS-LS3-1, HS-LS3-2

18. What is the name for a mutation that involves one nucleotide only?
    a. mutagen
    b. inversion
    c. point mutation
    d. translocation
19. When a chromosome undergoes a deletion mutation, information is
    a. repeated. **c**. reversed.
    b. lost. **d**. transferred.
20. A substance such as tobacco that can cause a genetic change is called a(n)
    a. polyploidy. **c**. mutagen.
    b. antigen. **d**. collagen.

21. Which kind of mutation is shown below?

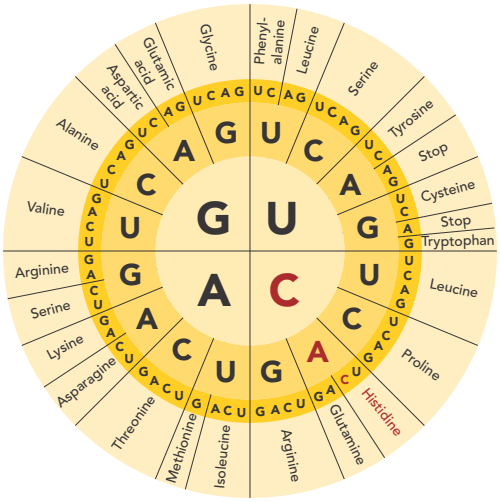


22. How can a mutation be beneficial to an organism?

CRITICAL THINKING

HS-LS1-1, HS-LS3-1, HS-LS3-2

Refer to the genetic code diagram below to answer questions 23–25.



23. **Analyze Data** Suppose you start with the DNA strand ACCGTCACT. What three amino acids does the complementary mRNA strand code for?

24. **Construct a Table** Construct a two-column table that presents the possible mRNA codons for the following amino acids: alanine, valine, and leucine.

25. **Analyze Data** Analyze the information in the table you constructed for question 24. How would a substitution mutation in the third nucleotide position of the codons for alanine and valine affect the resulting protein?

26. **Defend Your Claim** During what stage of meiosis will a failure of chromosomes to separate lead to polyploidy? Use evidence from the text to defend your claim.

27. **Construct an Explanation** Nitrous acid is a mutagen. It can react chemically with cytosine to change it to uracil in a DNA strand. Using your knowledge of DNA replication and base pairing, explain the effect of this mutagen on a strand of DNA that undergoes replication.

28. **Evaluate Evidence** In eukaryotes, the number of promoter sequences and enhancer sites and the TATA box make gene regulation far more complex than regulation in prokaryotes. Why is regulation in eukaryotes so much more complex?

29. **Evaluate Claims** A chromosomal mutation that occurs during meiosis may or may not be expressed in an organism's offspring. A similar mutation that only occurs during mitosis of a body cell will not be expressed in the organism's offspring. Evaluate these claims. Determine whether or not they are true, and explain your reasoning.

30. **Form a Hypothesis** *E. coli* bacteria need the amino acid tryptophan to survive. When tryptophan is present in its growth medium, *E. coli* is able to ingest it. However, tryptophan is not always available in the *E. coli's* environment. What are some questions you can ask regarding how *E. coli* might respond if tryptophan were not present in its growth medium? Form a hypothesis that you can test to answer one of your questions.

31. **Construct an Argument** A researcher identifies the nucleotide sequence AAC in a long strand of RNA inside a nucleus. In the genetic code, AAC codes for the amino acid asparagine. When that RNA becomes involved in protein synthesis, will asparagine necessarily appear in the protein? Use specific content to support your argument.

32. **Analyze** A mutation in the DNA of an organism changes one base sequence in a protein-coding region from CAC to CAT. What is the effect of the mutation on the final protein?

CROSSCUTTING CONCEPTS

33. **Patterns** The word *transcribe* means "to write out." The word *translate* means "to express in another language." Review the meanings of *transcription* and *translation* in genetics. Look for patterns in the meanings of these words. How do the technical meanings of these words relate to the everyday meanings of the words?

34. **Structure and Function** Describe how the sequence of nucleotides in mRNA codes for the amino acids of a protein. How can the insertion or deletion of even one nucleotide in mRNA cause significant changes to the protein that results?

MATH CONNECTIONS

Analyze and Interpret Data

CCSS.MATH.CONTENT.MP2

RNA is the genetic material of many viruses. Scientists analyzed RNA from four different types of viruses. The content of the four nitrogenous bases is shown below.

Base Percentages in Four Viruses

Virus	A	U	C	G
A	26.3	29.3	20.6	23.8
B	×	×	17.6	17.5
C	21.9	12.8	34.3	31.1
D	29.8	26.3	18.5	25.3

Use the data table to answer questions 35–37.

35. **Interpret Tables** Which of the four types of viruses is most likely to use double-stranded RNA as its genetic material? Explain how you reached your conclusion.

36. **Calculate** Based on the data, calculate the values in the two boxes labeled with an ×.

37. **Reason Quantitatively** How would the percentages of the four nitrogenous bases shown in the table compare to the percentages of the nitrogenous bases found in strands of DNA?

LANGUAGE ARTS CONNECTION

Write About Science

HS-LS3-1, CCSS.ELA-LITERACY.WHST.9-10.1, CCSS.ELA-LITERACY.WHST.9-10.8

38. **Write Arguments** A classmate tells you that comic books are full of superheroes with powers caused by mutations. Therefore, all mutations must be beneficial. Decide whether or not you agree. Write a paragraph to argue your position regarding the benefits or harm caused by mutations.

39. **Use Information** Explain what Hox genes are and what they control. Incorporate paraphrasing from the text into your explanation.

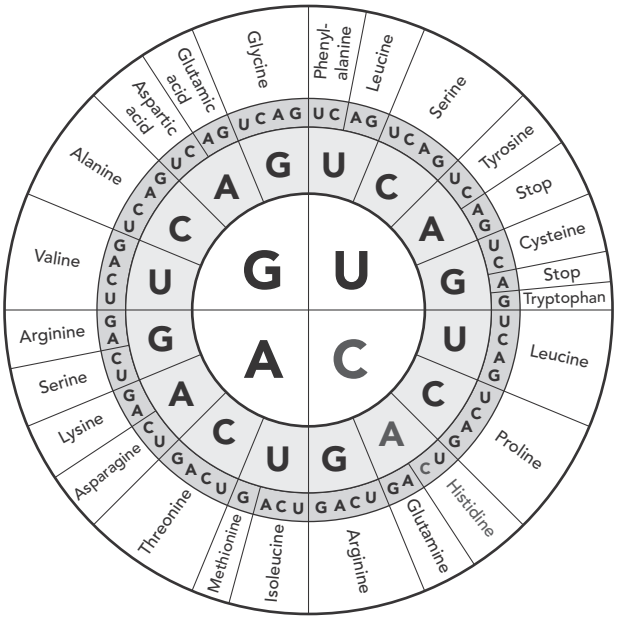
Read About Science

HS-LS3-1, CCSS.ELA-LITERACY.RST.9-10.1, CCSS.ELA-LITERACY.RST.9-10.9

40. **Corroborate** Research several different examples of epigenetics. Based on your understanding of epigenetics, explain how the patterns of expression are similar and how they are different.

END-OF-COURSE TEST PRACTICE

Questions 1–2 refer to the following diagram.



1. What is the significance of this genetic code?
   - **A**. It describes how DNA is transcribed to RNA.
   - **B**. It describes how RNA is translated to amino acids.
   - **C**. It describes how RNA is translated to genes.
   - **D**. It describes how proteins are translated to RNA.
   - **E**. It describes how RNA is translated to DNA.

2. Two scientists are both studying RNA. One scientist is studying RNA in mice, and the other is studying RNA in *E. coli* bacteria. Which of the following **best** describes how each scientist would use a genetic code?
   - **A**. Both scientists would use the same genetic code because all organisms have RNA.
   - **B**. Both scientists would use the same genetic code because in all organisms the code is read three bases at a time and in the same direction.
   - **C**. The scientists would use different genetic codes because different genes are expressed in mice and *E. coli*.
   - **D**. The scientist studying mice would use the genetic code for mice and the scientist studying *E. coli* would use the genetic code for *E. coli* because mice are more complex multicellular organisms.
   - **E**. The scientist studying mice would use the genetic code for eukaryotes and the scientist studying *E. coli* would use the genetic code for prokaryotes because they each have different types of chromosomes.

3. Human nerve cells and muscle cells have many structural and functional differences. What role does DNA play in these differences?
   - **A**. Nerve cells and muscle cells contain different DNA.
   - **B**. Nerve cells contain more DNA than muscle cells.
   - **C**. DNA in muscle cells is condensed into chromatids.
   - **D**. Muscle cells are more likely to have DNA mutations than nerve cells.
   - **E**. Transcription factors and gene expression is different in nerve cells and muscle cells.

ASSESSMENT

For additional assessment practice, go online to access your digital course.

If You Have Trouble With...			
Question	1	2	3
See Lesson	14.2	14.2	14.3
Performance Expectation	HS-LS1-1	HS-LS1-1	HS-LS3-1