

Protein Synthesis

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

CAN YOU EXPLAIN IT?

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



Gather Evidence

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



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

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



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

Introduction to Protein Synthesis

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

The Central Dogma

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

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



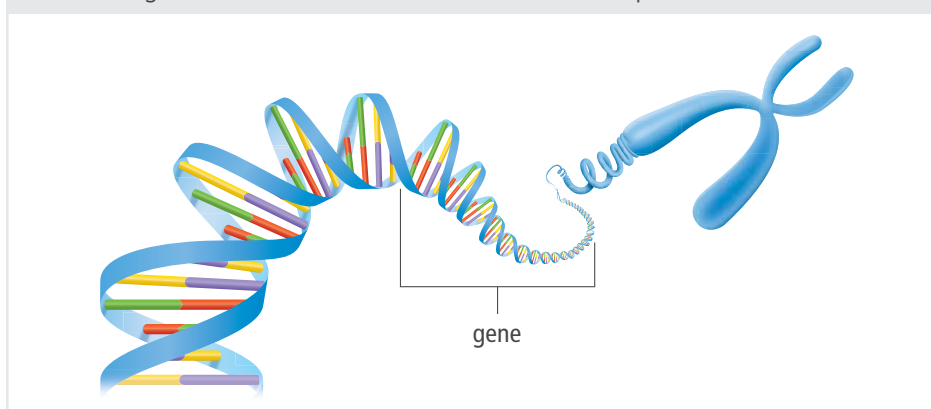
Model Create a flow chart to illustrate the flow of information in both protein synthesis and DNA replication.

Genes Code for Proteins

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

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

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



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

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

FIGURE 3: Proteins have many different functions.

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



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



Structure and Function

Protein Modeling

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



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

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



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

Stages of Protein Synthesis

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

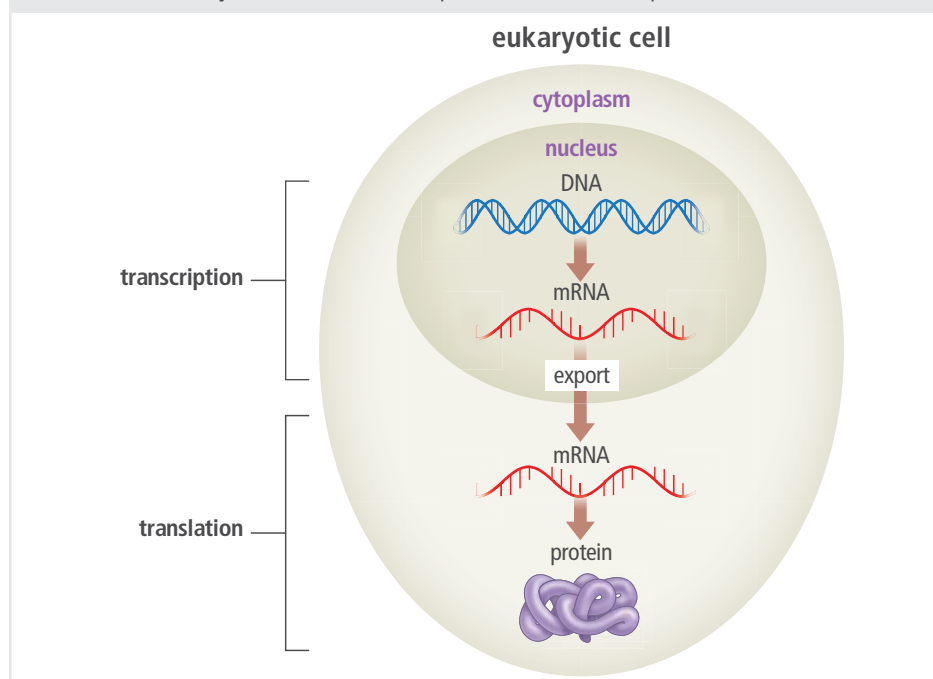


Predict Why do you think a “disposable copy” of the DNA code is necessary for protein synthesis?

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

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

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



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

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



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

Comparing DNA and RNA

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

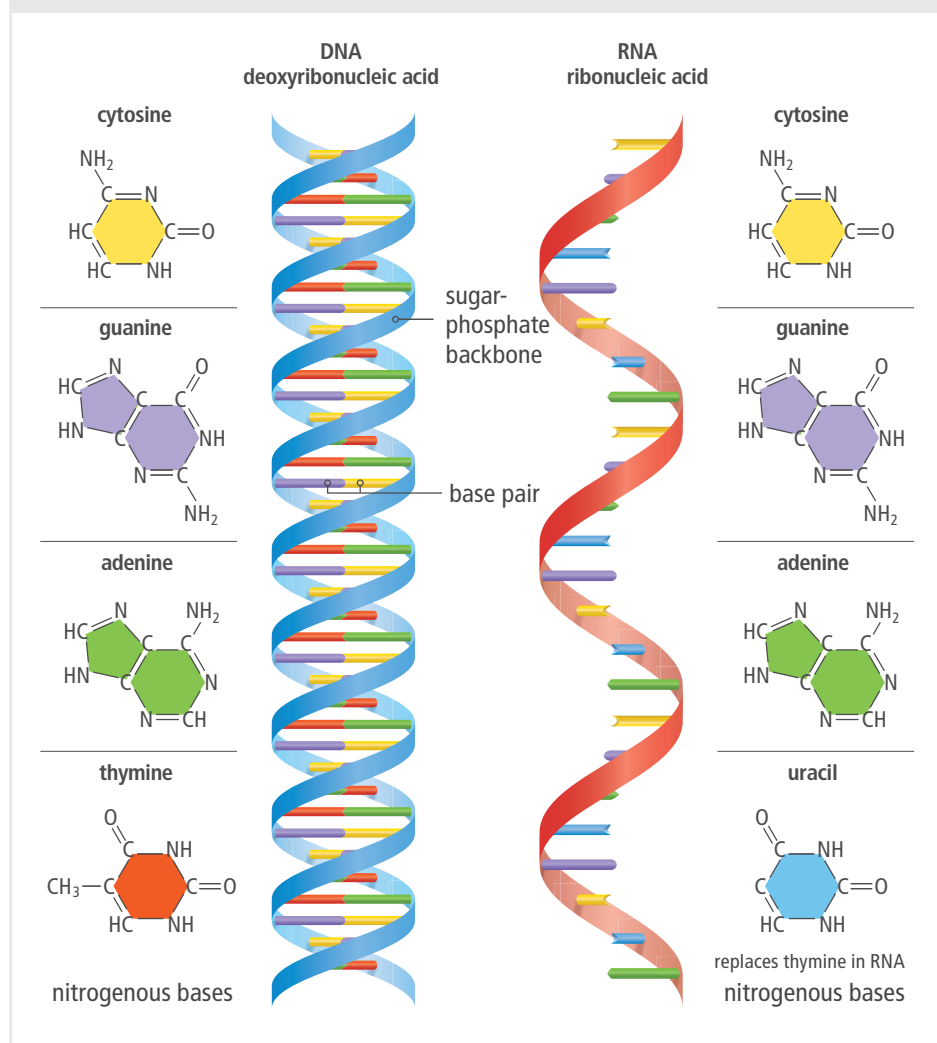


Language Arts

Connection

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

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



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



Explain Why is RNA necessary for protein synthesis?

Transcription

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

Steps of Transcription

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


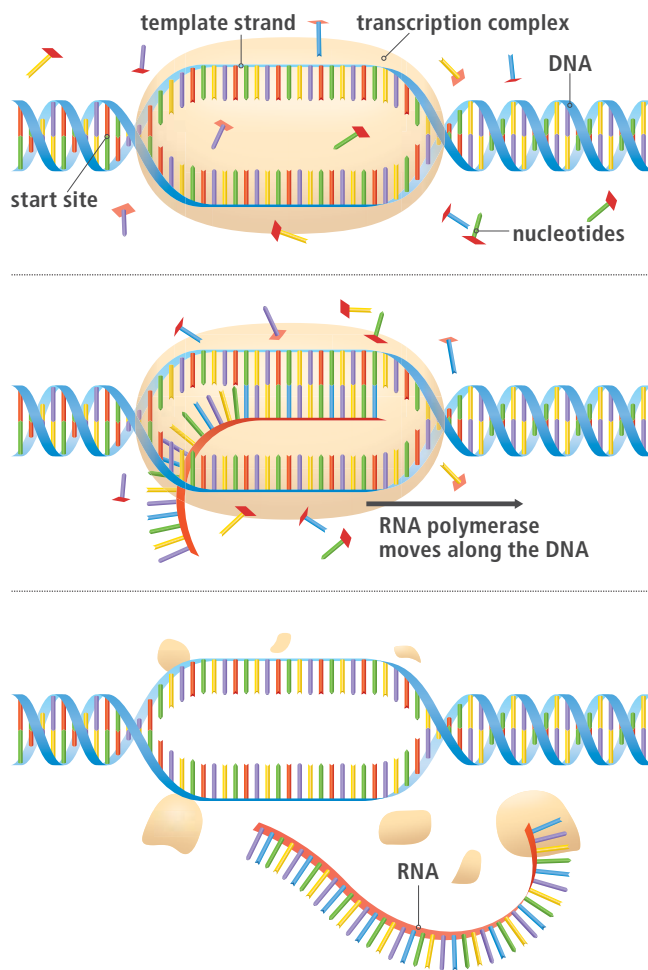
-  **Predict** Transcribe means to write. Why would we use the word transcribe to describe the process of making a complementary RNA sequence from a DNA template?

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

Explore Online 

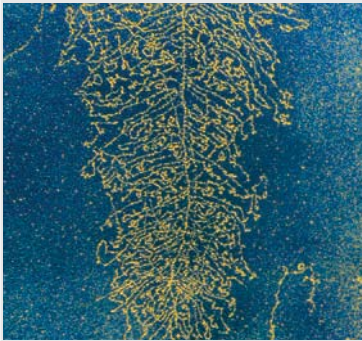


- 1 In eukaryotic cells, a large transcription initiation complex consisting of RNA polymerase and other proteins assembles on the DNA strand and begins to unwind a segment of the DNA molecule. The complex assembles at a specific sequence of nucleotides along the DNA molecule called a promoter.
- 2 RNA polymerase, using one strand of DNA as a template, strings together a complementary strand of RNA nucleotides. RNA base pairing follows the same rules as DNA base pairing, except that uracil, not thymine, pairs with adenine. So, U pairs with A and G pairs with C. The growing RNA strand hangs freely as it is transcribed, and the DNA helix zips back together.
- 3 Transcription continues until an entire gene has been converted to RNA. The RNA strand detaches completely from the DNA.



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

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




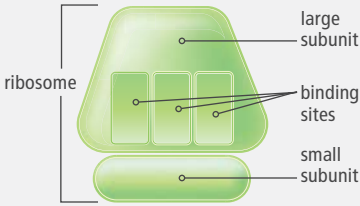
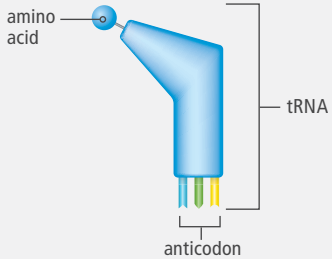
Transcription can produce hundreds or thousands of copies of mRNA depending on the cell's needs. Transcription enables a cell to adjust to changing demands by making a single-stranded complement of only a segment of DNA, and only when that particular segment is needed. Many RNA molecules can be transcribed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



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

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

FIGURE 9: Transcription produces three main types of RNA.

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



Model Write a complementary mRNA sequence for the DNA sequence below. Remember that RNA contains uracil instead of thymine.
DNA sequence: TCA GGT ACG CTT

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



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

Translation

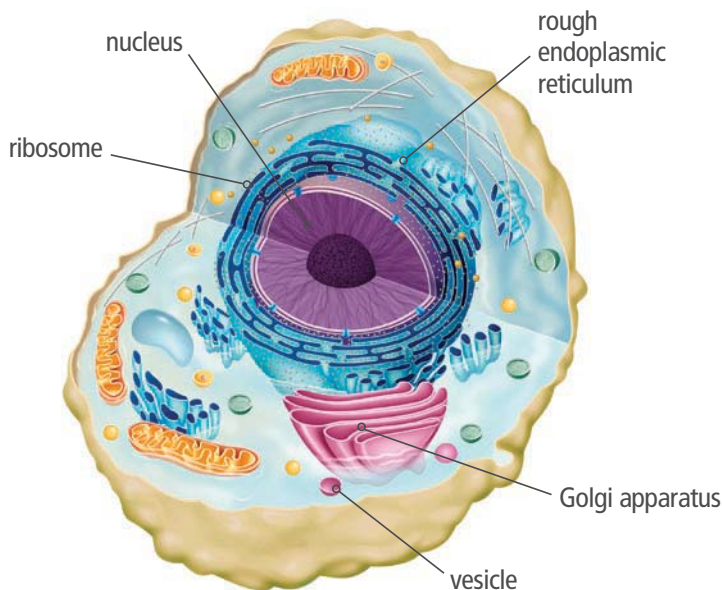
In order to complete protein synthesis, the language of mRNA must be translated into the language of proteins. How does a language consisting of only four characters translate into a language of 20 amino acids? Just as letters are strung together in the English language to make words, nucleotides are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

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

Ribosomes

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

FIGURE 10: Animal Cell



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



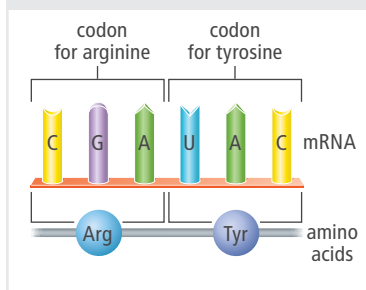
Collaborate In everyday language, translation means to express words in another language. Give an example of a message that would need to be translated.



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

Codons and Amino Acids

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



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

Explore Online

Hands-On Activity

Modeling Protein Synthesis and Mutations

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

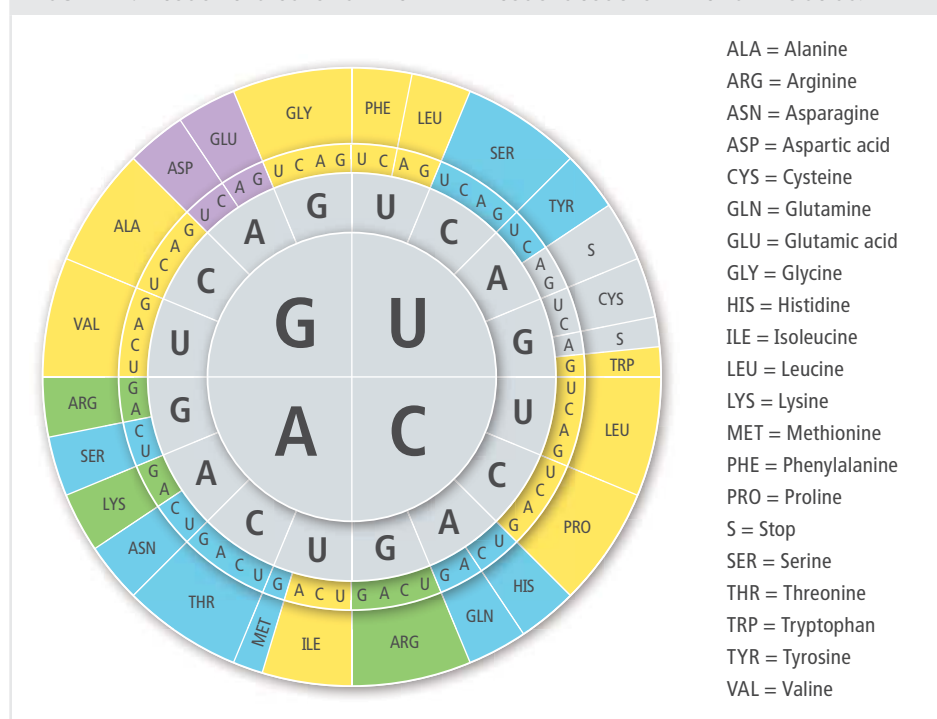
The translation of RNA into protein is similar to what happens in a computer code. The information encoded in the nucleic acids of an mRNA molecule is “read” in groups of three nucleotides called codons. This is similar to the way a computer interprets the zeroes and ones of binary code strings into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



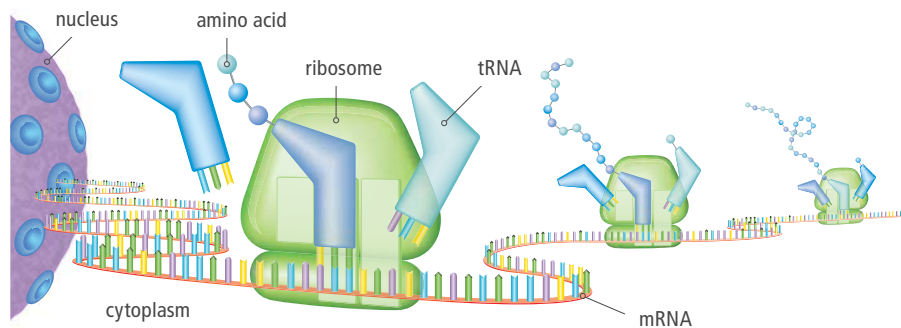
Math Connection Suppose an mRNA molecule in the cytoplasm had 300 nucleotides. How many amino acids would be in the resulting polypeptide?

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

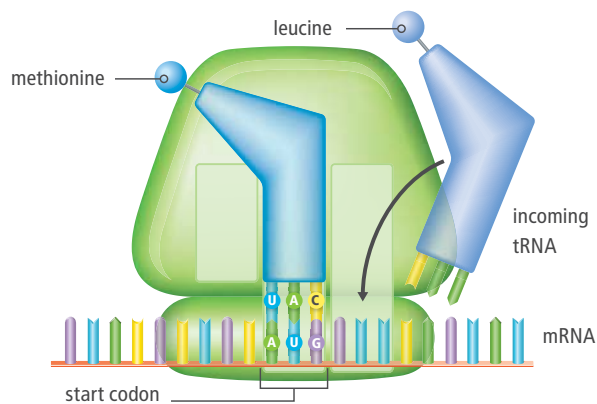
FIGURE 12: A codon chart shows which mRNA codons code for which amino acids.



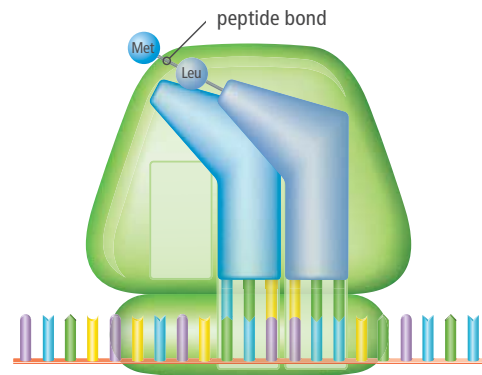
The genetic code is shared by almost all living organisms, as well as viruses. That means, for example, that the codon UUU codes for phenylalanine when that codon occurs in an armadillo, a cactus, a yeast, or a human. The common nature of the genetic code suggests that organisms arose from a common ancestor.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

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

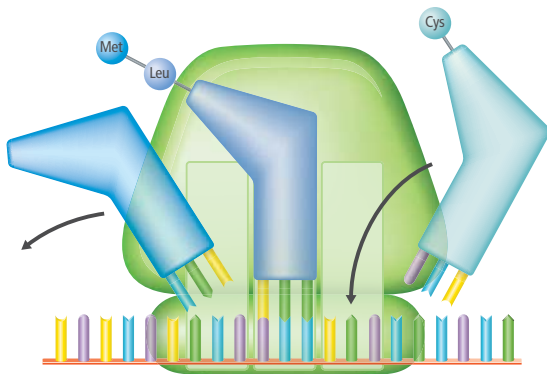
- 1 Before translation begins, a small ribosomal subunit binds to an mRNA strand in the cytoplasm. Then a tRNA with methionine attached binds to the AUG start codon. This binding signals a large ribosomal subunit to join. The ribosome pulls the mRNA strand through itself one codon at a time. The tRNA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



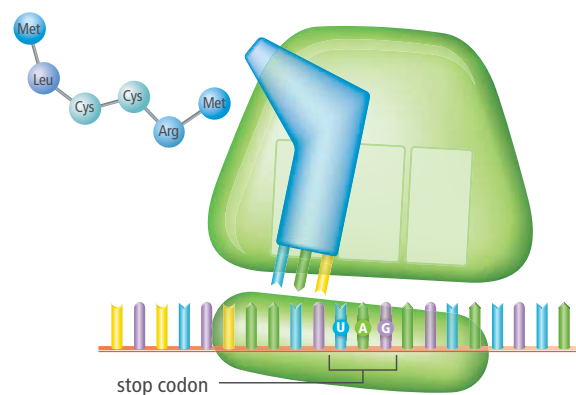
- 2 The exposed codon in the first site attracts a complementary tRNA molecule carrying an amino acid. The tRNA pairs with the mRNA codon, bringing it very close to the other tRNA molecule.



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



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



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



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

Mutations and Proteins

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



Structure and Function

FIGURE 14: Mutations alter nucleotide sequences.

Original DNA Sequence

TAC AGA GGC CGT

Mutated DNA Sequence

TAC AGT GAC CGT



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

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



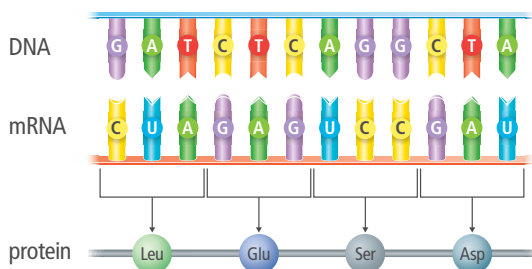
Analyze Could there be a frameshift mutation that would not affect the structure and function of the resulting protein? Explain your answer.

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

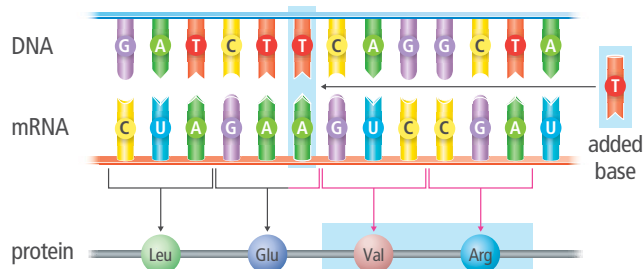
In an insertion mutation, an extra nucleotide is added into the DNA sequence. In a deletion mutation, a nucleotide is deleted from the DNA sequence. Because mRNA is read in groups of three nucleotides, the insertion or deletion of a nucleotide can affect the entire resulting amino acid sequence. For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

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

normal



frameshift mutation (insertion)



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

Language Arts Connection

Making Synthetic Cells

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

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

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

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

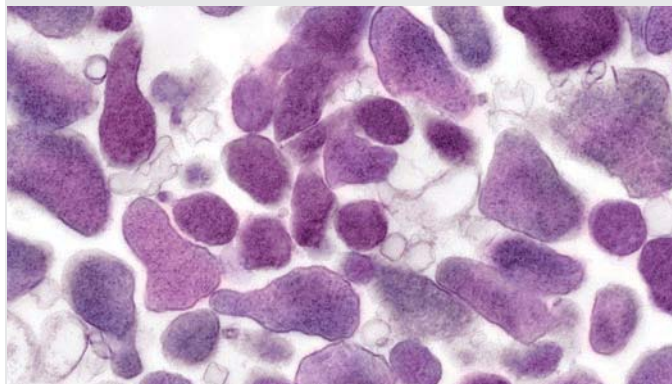
The slow growth rate of *M. genitalium* led the team to switch to a new species of bacteria called *Mycoplasma mycoides*. The scientists synthesized the new species’ genome and implanted it into a different species of bacterium. They had reached their goal of making a synthetic cell. However, the genome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

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

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

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

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



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



MODELING PROTEIN SYNTHESIS AND MUTATIONS



EXPLORING PROTEIN CRYSTALLIZATION

Go online to choose one of these other paths.

Lesson Self-Check

CAN YOU EXPLAIN IT?

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



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



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

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

CHECKPOINTS

Check Your Understanding

- A student is planning to draw a model of DNA and a model of RNA. Which of the following should the student include in the DNA model and NOT the RNA model?
 - a double helix
 - the nucleotide uracil
 - the sugar ribose
 - a phosphate group
- Which of the following is evidence that would support the claim that DNA has been transcribed into RNA?
 - A temporary, complementary copy of the DNA has been produced.
 - An exact, permanent copy of the DNA has been produced.
 - A complementary, permanent copy of RNA has been produced and it replaces DNA.
- Which statement correctly compares the impact of frameshift mutations and point mutations on polypeptides?
 - Point mutations have a greater impact because they always change the resulting protein.
 - Frameshift mutations have a greater impact because they always substitute the first nucleotide in a codon.
 - Frameshift mutations have a greater impact because they shift the entire codon sequence following them.
 - Point mutations have a greater impact because they always cause a change in the amino acid sequence.
- Place these steps in order to describe the process of transcription.
 - RNA polymerase uses the DNA strand as a template to synthesize a complementary strand of RNA.
 - The RNA strand grows until an entire gene has been transcribed.
 - The complex of RNA polymerase and proteins breaks apart.
 - The DNA is unwound and a specific sequence of nucleotides is sequenced along the promoter.
 - A large complex consisting of RNA polymerase and other proteins assembles on the DNA strand.
- Which flow chart best summarizes the process of protein synthesis?
 - rRNA → DNA → mRNA
 - Protein → mRNA → DNA
 - mRNA → DNA → protein
 - DNA → mRNA → protein
- Fill in the correct terms to complete this statement about eukaryotes. Some terms may be used more than once.

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

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

MAKE YOUR OWN STUDY GUIDE



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

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

Remember to include the following information in your study guide:

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

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