DNA, RNA, and Protein Synthesis

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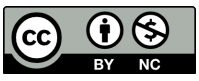


CHAPTER 1

DNA, RNA, and Protein Synthesis

Lesson Objectives

- Explain the chemical composition of DNA.
- Explain how DNA synthesis works.
- Explain how proteins are coded for and synthesized.
- Describe the three types of RNA and the functions of each.

Check Your Understanding

- What is the purpose of DNA?
- When is DNA replicated?

Vocabulary

- amino acid
- DNA
- DNA replication
- double helix
- gene
- mutagen
- mutation
- nucleotide
- RNA
- semiconservative replication
- transcription
- translation

What is DNA?

DNA, is the material that makes up our chromosomes and stores our genetic information. When you build a house, you need a blueprint, a set of instructions that tells you how to build. The DNA is like the blueprint for living organisms. The genetic information is a set of instructions that tell your cells what to do.

DNA is an abbreviation for deoxyribonucleic acid. As you may recall, nucleic acids are a type of macromolecule that store information. The *deoxyribo* part of the name refers to the name of the sugar that is contained in DNA, deoxyribose. DNA may provide the instructions to make up all living things, but it is actually a very simple molecule. DNA is made of a long chain of nucleotides.

Nucleotides are composed of 3 main parts:

1. Phosphate group
2. 5-carbon sugar
3. Nitrogen-containing base

The only difference between each nucleotide is the identity of the base. There are only four possible bases that make up each DNA nucleotide: adenine (A), guanine (G), thymine (T), and cytosine (C).

The various sequences of these four bases make up the genetic code of your cells. It may seem strange that there are only four letters in the "alphabet" of DNA. But since your chromosomes contain millions of nucleotides, there are many, many different combinations possible with those four letters.

But how do all these pieces fit together? James Watson and Francis Crick won the Nobel Prize in 1962 for piecing together the structure of DNA. Together with the work of Rosalind Franklin and Maurice Wilkins, they determined that DNA is made of two strands of nucleotides formed into a **double helix**, or a two-stranded spiral, with the sugar and phosphate groups on the outside, and the paired bases connecting the two strands on the inside of the helix (**Figure** 1.1 and **Figure** 1.2).

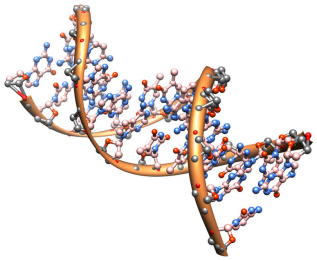


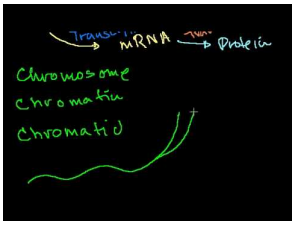
FIGURE 1.1

DNA's three-dimensional structure is a double helix. The hydrogen bonds between the bases at the center of the helix hold the helix together.

Base-Pairing

The bases in DNA do not pair randomly. When Erwin Chargaff looked closely at the bases in DNA, he noticed that the percentage of adenine (A) in the DNA always equaled the percentage of thymine (T), and the percentage of guanine (G) always equaled the percentage of cytosine (C). Watson and Crick's model explained this result by suggesting that A always pairs with T and G always pairs with C in the DNA helix. Therefore A and T, and G and C, are "complementary bases," or bases that always pair together. For example, if one DNA strand reads ATGCCAGT, the other strand will be made up of the complementary bases: TACGGTCA.

The vocabulary of DNA, including chromosomes, chromatids, chromatin, transcription, translation, and replication, is discussed at http://www.youtube.com/watch?v=s9HPNwXd9fk (18:23).



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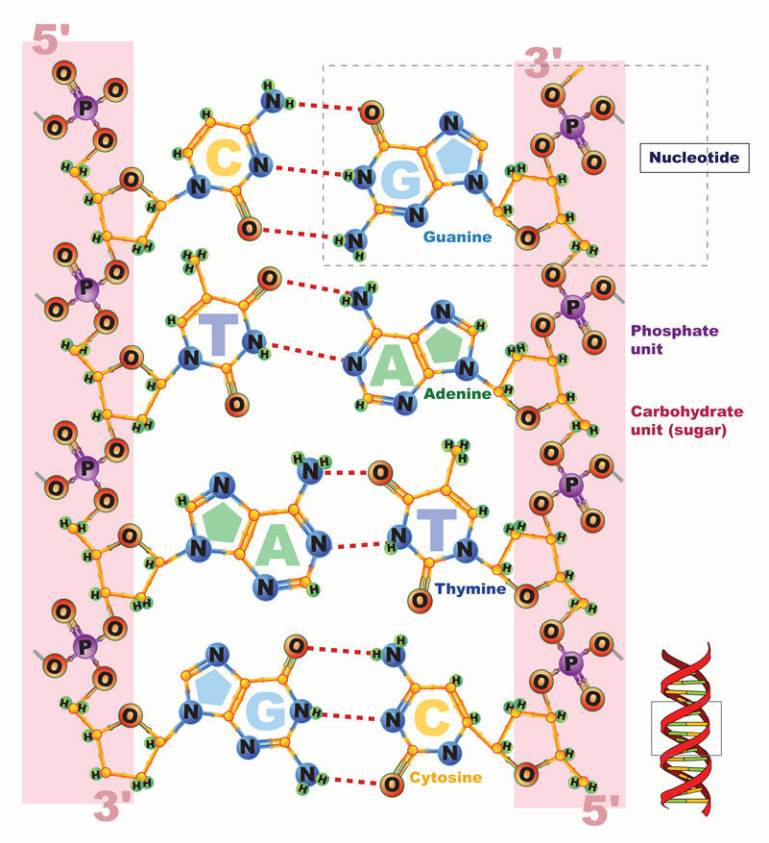


FIGURE 1.2

The chemical structure of DNA includes a chain of nucleotides consisting of a 5-carbon sugar, a phosphate group, and a nitrogen base. Notice how the sugar and phosphate form the backbone of DNA (one strand in blue), with the hydrogen bonds between the bases joining the two strands.

DNA Replication

The base pairing rules are crucial for the process of replication. **DNA replication** occurs when DNA is copied to form an identical molecule of DNA. DNA replication happens before cell division. Below are the steps involved in DNA replication:

1. The DNA helix unwinds like a zipper, as the bonds between the base pairs are broken.
2. The two single strands of DNA then each serve as a template for a new stand to be created. Using DNA as a template means that the bases are placed in the right order because of the base pairing rules. If ATG is on the "template strand," then TAC will be on the new DNA strand.
3. The new set of nucleotides then join together to form a new strand of DNA. The process results in two DNA molecules, each with one old strand and one new strand of DNA.

This process is known as **semiconservative replication** because one strand is conserved (kept the same) in each new DNA molecule (**Figure** 1.3).

Protein Synthesis

The DNA sequence contains the instructions to make units called amino acids, which are assembled in a specific order to make proteins. In short, DNA contains the instructions to create proteins. Each strand of DNA has many

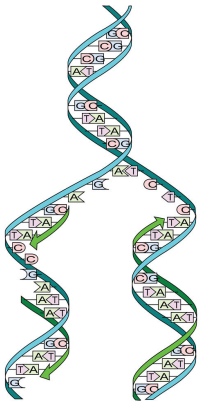


FIGURE 1.3

DNA replication occurs when the DNA strands “unzip”, and the original strands of DNA serve as a template for new nucleotides to join and form a new strand.

separate sequences that code for a specific protein. Units of DNA that contain code for the creation of one protein are called **genes.** An overview of protein synthesis can be seen at this animation: http://www.biostudio.com/demo_freeman_protein_synthesis.htm

Cells Can Turn Genes On or Off

There are about 22,000 genes in every human cell. Does every human cell have the same genes? Yes. Does every human cell use the same genes to make the same proteins? No. In a multicellular organism, such as us, cells have specific functions because they have different proteins. They have different proteins because different genes are expressed in different cell types.

Imagine that all of your genes are "turned off." Each cell type only "turns on" (or expresses) the genes that have the code for the proteins it needs to use. So different cell types "turn on" different genes, allowing different proteins to be made, giving different cell types different functions.

Three Types of RNA

DNA contains the instructions to create proteins, but it does not make proteins itself. DNA is located in the nucleus, while proteins are made on ribosomes in the cytoplasm. So DNA needs a messenger to bring its instructions to a ribosome located outside of the nucleus. DNA sends out a message, in the form of **RNA** (ribonucleic acid), describing how to make the protein.

There are three types of RNA directly involved in protein synthesis:

- Messenger RNA (mRNA) carries the instructions from the nucleus to the cytoplasm.
- The other two forms of RNA, ribosomal RNA (rRNA) and transfer RNA (tRNA) are involved in the process of ordering the amino acids to make the protein.

All three RNAs are nucleic acids, made of nucleotides, similar to DNA. The RNA nucleotide is different from the DNA nucleotide in the following ways:

- RNA contains a different kind of sugar, called ribose.
- In RNA, the base uracil (U) replaces the thymine (T) found in DNA.
- RNA is a single strand.

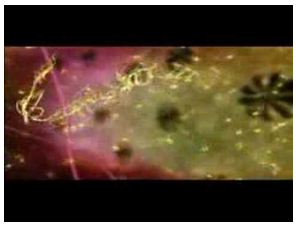
Transcription

mRNA is created by using DNA as a template. The process of constructing an mRNA molecule from DNA is known as **transcription** (**Figure** 1.4 and **Figure** 1.5). The double helix of DNA unwinds and the nucleotides follow basically the same base pairing rules to form the correct sequence in the mRNA. This time, however, U pairs with each A in the DNA. In this manner, the genetic code is passed on to the mRNA.

Two multimedia links of protein synthesis are provided below.

- http://www-class.unl.edu/biochem/gp2/m_biology/animation/gene/gene_a2.html

Transcription and Translation can be viewed at http://www.youtube.com/watch?v=41_Ne5mS2ls (4:06).



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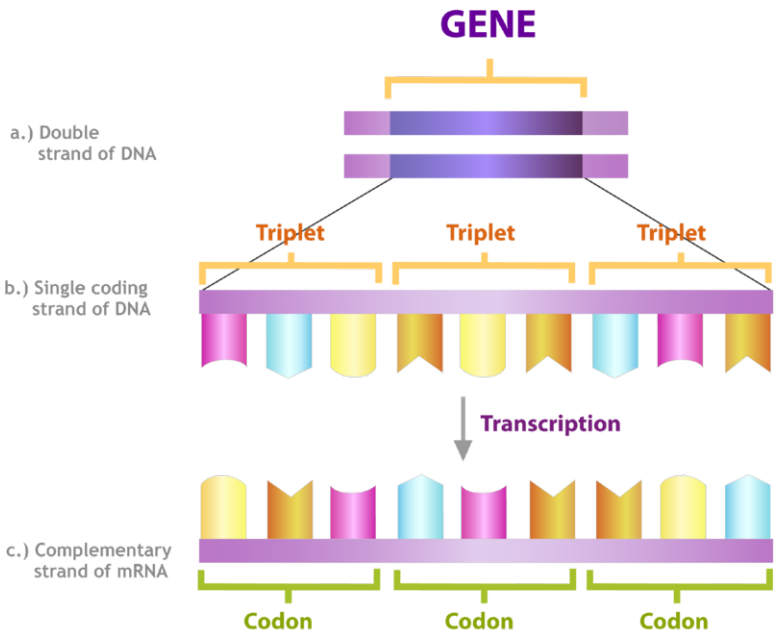

FIGURE 1.4

Each gene (a) contains triplets of bases (b) that are transcribed into RNA (c). Every triplet, or codon, encodes for a unique amino acid.

Translation

The mRNA is directly involved in the protein-making process. mRNA tells the ribosome (**Figure** 1.6) how to create a protein. The process of reading the mRNA code in the ribosome to make a protein is called **translation** (**Figure** 1.7). Sets of three bases, called codons, are read in the ribosome, the organelle responsible for making proteins.

The following are the steps involved in translation:

1. mRNA travels to the ribosome from the nucleus.

FIGURE 1.5

Base-pairing ensures the accuracy of transcription. Notice how the helix must unwind for transcription to take place.

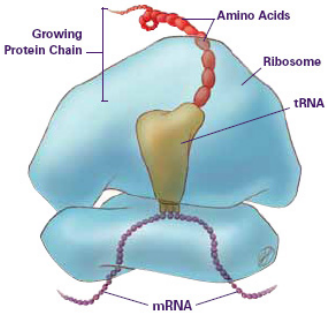

FIGURE 1.6

Ribosomes translate RNA into a protein with a specific amino acid sequence. The tRNA binds and brings to the ribosome the amino acid encoded by the mRNA. Ribosomes are made of rRNA and proteins.

2. The base code in the mRNA determines the order of the amino acids in the protein. The genetic code in mRNA is read in "words" of three letters (triplets), called **codons.** There are 20 amino acids and different codons code for different ones. For example, GGU codes for the amino acid glycine, while GUC codes for valine.
3. tRNA reads the mRNA code and brings a specific amino acid to attach to the growing chain of amino acids. Each tRNA carries only one type of amino acid and only recognizes one specific codon.
4. tRNA is released from the amino acid.
5. Three codons, UGA, UAA, and UAG, indicate that the protein should stop adding amino acids. They are called "stop codons" and do not code for an amino acid. Once tRNA comes to a stop codon, the protein is set free from the ribosome.

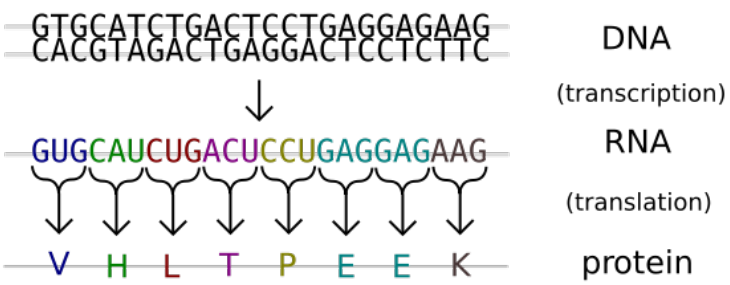

FIGURE 1.7

This summary of how genes are expressed shows that DNA is transcribed into RNA, which is translated in turn to protein.

The chart in **Figure** 1.8 is used to determine which amino acids correspond to which codons. An interactive activity for transcribing and translating a gene can be found at http://learn.genetics.utah.edu/units/basics/transcribe/ .

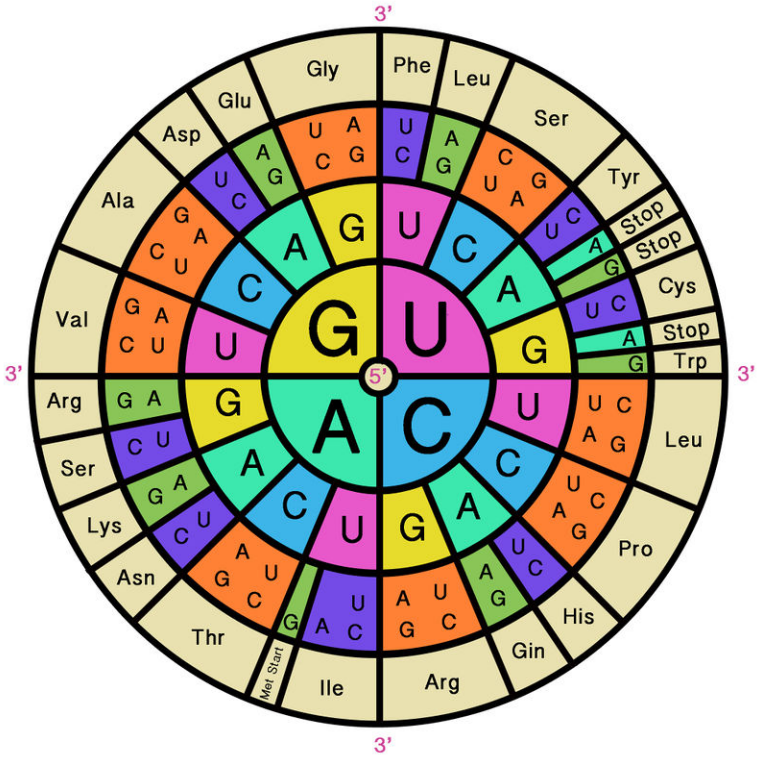

FIGURE 1.8

This chart shows the genetic code used by all organisms. For example, an RNA codon reading GUU would encode for a valine (Val) according to this chart. Start at the center for the first base of the three base codon, and work your way out. Notice for valine, the second base is a U and the third base of the codon may be either a G, C, A, or U. Similarly, glycine (Gly) is encoded by a GGG, GGA, GGC, and GGU.

Mutations

The process of DNA replication is not always 100% accurate, and sometimes the wrong base is inserted in the new strand of DNA. A permanent change in the sequence of DNA is known as a **mutation**. Small changes in the DNA sequence are usually point mutations, which is a change in a single nucleotide. A mutation may have no effect. Sometimes, a mutation can cause the protein to be made incorrectly, which can affect how well the protein works, or whether it works at all. Usually the loss of a protein function is detrimental to the organism.

However, in rare circumstances, the mutation can be beneficial. For example, suppose a mutation in an animal's DNA causes the loss of an enzyme that makes a dark pigment in the animal's skin. If the population of animals has moved to a light colored environment, the animals with the mutant gene would have a lighter skin color and be better camouflaged. So in this case, the mutation is beneficial.

Mutations may also occur in chromosomes. Possible types of mutations in chromosomes (**Figure** 1.9) include:

1. Deletion: When a segment of DNA is lost, so there is a missing segment in the chromosome.
2. Duplication: When a segment of DNA is repeated, creating a longer chromosome.
3. Inversion: When a segment of DNA is flipped and then reattached to the chromosome.
4. Insertion: When a segment of DNA from one chromosome is added to another, unrelated chromosome.
5. Translocation: When two segments from different chromosomes change positions.

If a single base is deleted (called a point mutation), there can be huge effects on the organism because this may cause

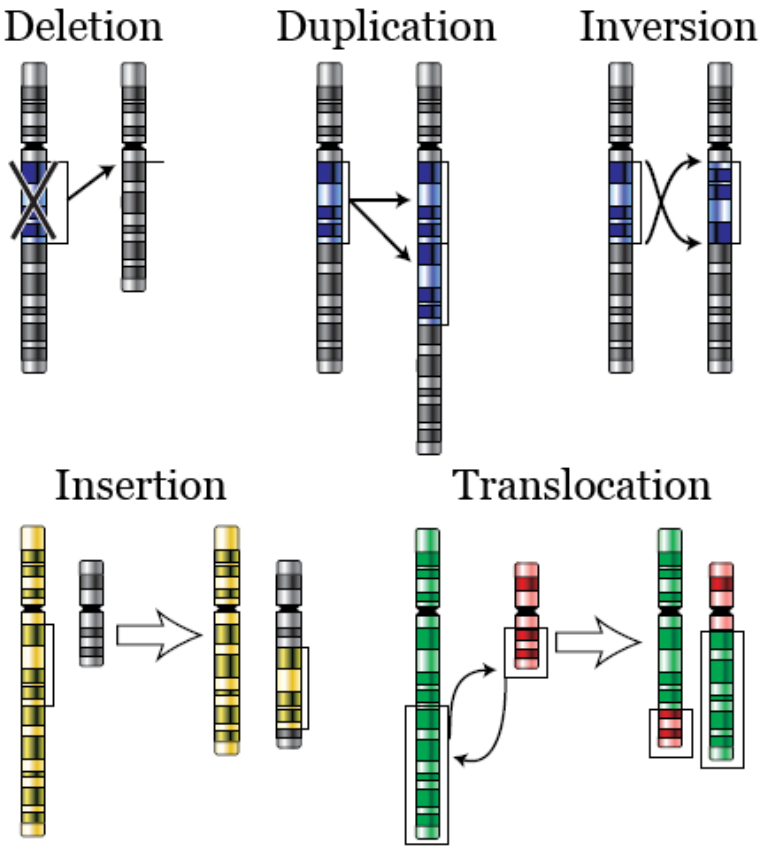

FIGURE 1.9

Mutations can arise in DNA through deletion, duplication, inversion, insertion, and translocation within the chromosome.

a "frameshift mutation." Remember that the bases are read in groups of three by the tRNA. If the reading frame gets off by one base, the resulting sequence will consist of an entirely different set of codons. The reading of an mRNA is like reading three letter words of a sentence. Imagine you wrote “the big dog ate the red cat”. If you take out the second letter from "big", the frame will be shifted so now it will read “ the bgd oga tet her edc at.” One single deletion makes the whole “sentence” impossible to read.

Many mutations are not caused by errors in replication. Mutations can happen spontaneously and they can be caused by **mutagens** in the environment. Some chemicals, such as those found in tobacco smoke, can be mutagens. Sometimes mutagens can also cause cancer. Tobacco smoke, for example, is often linked to lung cancer.

Lesson Summary

- DNA stores the genetic information of the cell in the sequence of its 4 bases: adenine, thymine, guanine, and cytosine.
- The information in a small segment of DNA, a gene, is sent by mRNA to the ribosome to synthesize a protein.
- Within the ribosome, tRNA reads the mRNA in sets of three bases (triplets), called codons, which encode for the specific amino acids that make up the protein.
- A mutation is a permanent change in the sequence of bases in DNA.

Review Questions

Recall

1. What is a nucleotide made out of?
2. Describe the process of DNA replication.
3. What is made in the process of transcription?
4. What is made in the process of translation?
5. Name a mutagen.

Apply Concepts

6. Translate the following segment of DNA into RNA: AGTTC
7. Write the complimentary DNA nucleotides to this strand of DNA: GGTCCA
8. Nucleotides are subunits of which two macromolecules?
9. Amino acids are subunits that make up what macromolecule?
10. How does RNA encode for proteins?

Critical Thinking

11. How does a mutation in a strand of DNA affect translation and transcription?
12. Given the DNA sequence, ATGTTAGCCTTA, what is the mRNA sequence? What is the amino acid sequence?

Further Reading / Supplemental Links

- http://nobelprize.org/educational_games/medicine/dna_double_helix/readmore.html
- http://learn.genetics.utah.edu/units/basics/builddna/
- http://sickle.bwh.harvard.edu/scd_background.html

Points to Consider

- Your cells have "proofreaders" that replace mismatched pairs that occurred during DNA synthesis. How would that affect the rate of mutation in your body?
- There are many diseases due to mutations in the DNA. These are known as genetic diseases, and many can be passed onto the next generation. Think about how a single base change cause a huge medical problem.
- Your DNA contains the instructions to make you. So is everyone's DNA different? Can it be used to distinguish individuals, like a fingerprint?

References

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