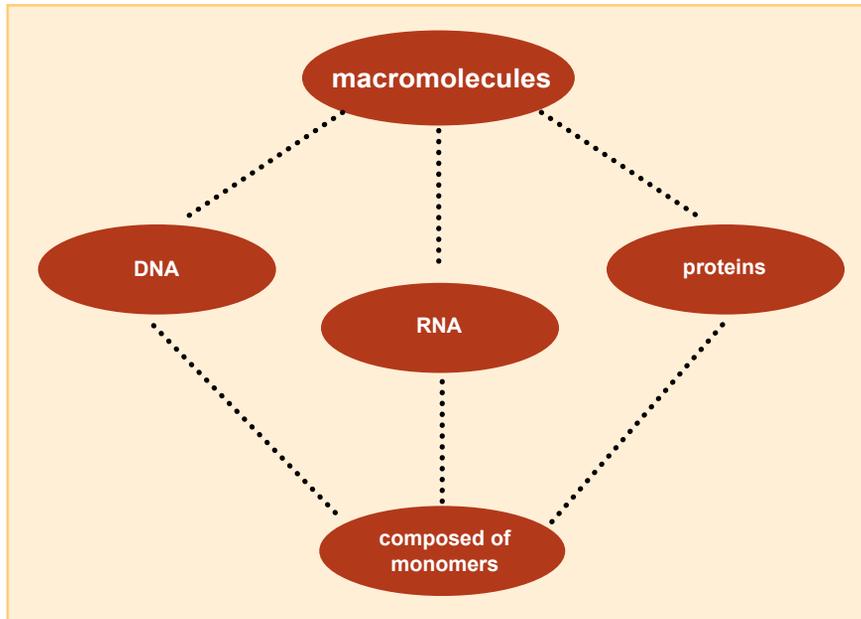


Nucleic Acids and Proteins



Essential Questions

- What is a monomer, and what relation does it have to the structure and function of polymers?
- How do nucleic acid monomers influence the function of DNA and RNA?
- How does the sequence of an amino acid determine the three-dimensional structure of the protein?
- What does directionality mean when referring to nucleic acids and proteins?

Keywords

amino acid
 dehydration synthesis
 fatty acids
 monomer
 monosaccharides
 non-polar molecule
 nucleotide
 nucleic acid
 peptide bond
 polar molecule
 polymer
 protein
 rRNA

Set the Stage

Although one missing amino acid in a polypeptide or the wrong nucleotide in a nucleic acid sequence are small differences, they can have serious consequences for an organism. The wrong nucleotide in DNA or RNA can result in the wrong codon being used during the translation process and then the wrong amino acid being inserted into the final sequence. When the primary sequence of a protein is wrong, the protein will not fold in the same way it would have, and ultimately the function of the protein will be different or nonexistent. This can cause serious problems in a biological system that is dependent on thousands of pieces working harmoniously together for the wellbeing of the organism. If one part does not work, others might not either, the way a car would not work without a steering wheel.

An example of a problem that missing amino acids or wrong nucleotides can



Figure 1. Sickle-shaped red blood cells are the result of a single base-change mutation.

cause in humans is the disease of sickle-cell anemia, a genetic blood disorder that produces abnormal red blood cells with a tendency to form unwanted clots in the blood stream due to their sickle shape. This disease is the result of one monomer, glutamic acid, being substituted for the amino acid valine in the primary sequence of hemoglobin. It is only one example of the thousands of genetic disorders that can occur when one monomer is out of place.

Macromolecules are polymers made of connected monomers.

All living things are constructed primarily from four major macromolecules: nucleic acids, proteins, lipids, and carbohydrates. **Nucleic acid** is important in storing, transmitting, and making useful the information necessary for the processes of life. **Protein** is composed of amino acids that are important for life functions. Lipids are composed of fats, oils, phospholipids, steroids, and waxes. Carbohydrates are large organic molecules made from carbon, oxygen, and hydrogen.

nucleic acid a macromolecule important in storing, transmitting, and making useful the information necessary for the processes of life

protein a macromolecule composed of amino acids that are important for life functions

The molecules nucleic acids, proteins, lipids, and carbohydrates are referred to as “macro” because of the large number of atoms used in their construction and because of their large molecular weight (often over 100,000 daltons). The majority of macromolecules are **polymers** (PAH-luh-muhr), large molecules of repeating groups of molecularly identical, nearly identical, or closely related subunits. These polymer subunits are known as **monomers** (MAH-nuh-muhr). Within any particular cell, thousands of different macromolecules can be found carrying out many important functions—all contributing to the process of life.

Monomers are important to polymer structure and function.

Each class of macromolecule is made up of different types of monomers. Nucleic acid monomers are called **nucleotides**; protein monomers are called **amino acids**; lipid monomers are called **fatty acids**; and carbohydrate monomers are called **monosaccharides** (MAH-nuh-SA-kuh-riyd). All types of monomers are organic molecules, meaning that they contain carbon-to-carbon bonds. Commonly the monomers will have many carbon atoms bonded together repeatedly to form chains, resembling the structure of fatty acids. These chains are referred to as carbon “backbones” because of their repetitive appearance. Other times the carbon atoms may take the form of rings, as they do in monosaccharides and nucleotides.

In addition to the numerous carbon atoms and bonds in these molecules, monomers may contain arrangements of atoms and bonds, called functional groups, which influence the function of the polymers in unique ways. A common functional group found in amino acids is the amino group -NH_2 (**Figure 2**). Other commonly occurring functional groups include carboxyl groups (-COOH) in amino acids, methyl groups (-CH_3), and phosphate groups (-PO_3) in nucleic acids. The varying chemical properties of these functional groups, according to how they are attached to the various carbon rings and chains, are the reason that different monomers have unique characteristics.

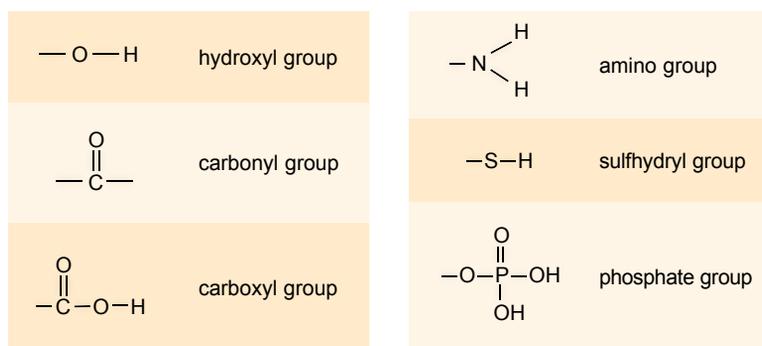


Figure 2. Functional groups are groups of atoms that attach to carbon backbones. Each group has different chemical properties that influence chemical interactions. These six functional groups are commonly found in biological chemicals.

polymer large molecules of repeating groups of molecularly identical subunits

monomer building block molecules for polymers

nucleotide a subunit of a nucleic acid that consists of a phosphate group, a five-carbon sugar, and a nitrogenous base

amino acid the organic molecules from which proteins are made

fatty acids the organic molecules that serve as the units from which lipids are made

monosaccharides the organic molecules from which carbohydrates are made

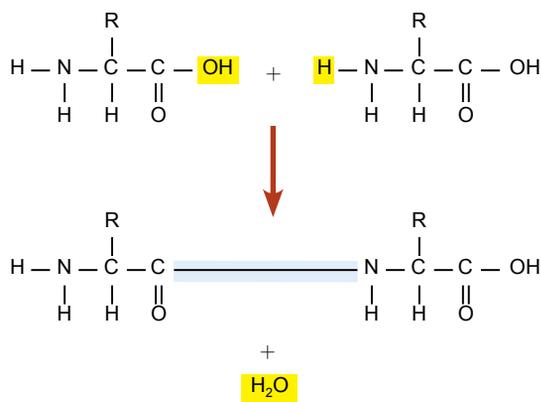


Figure 3. A dehydration synthesis reaction occurs when an $-\text{OH}$ group is removed from one chemical and an $-\text{H}$ is removed from another. The two chemicals are bound together with a covalent bond, and a molecule of H_2O is produced.

Ultimately, the structures of the monomers determine the characteristics and function of polymers and the organism as a whole. The structure affects the order, orientation, and environmental interaction of the larger macromolecule. The macromolecule properties that arise due to these monomer characteristics are called emergent properties.

Since monomer building blocks constitute the structures of all life on earth, and since structure directly influences the function of organisms, this lesson will devote significant time to these important molecules and the macromolecules they construct.

Connecting and disconnecting monomers occurs through condensation and hydrolysis reactions.

An important part of biology is knowing what pieces make up macromolecules. How they are put together and taken apart is also important because macromolecules are frequently constructed and deconstructed with major implications for the function of organisms. When you digest food, for example, the cells lining your digestive tract absorb monomers of the lipids, carbohydrates, and proteins you just ate and use them as building blocks to construct their own macromolecules. This utilization is possible because of two opposing chemical reactions that utilize monomers, water, and enzymes.

A reaction called **dehydration synthesis**, or condensation, connects two monomers. This process occurs when an enzyme removes an $-\text{OH}$ group from the end of one monomer and an $-\text{H}$ atom from another monomer. The $-\text{OH}$ and $-\text{H}$ join together, creating water, while the two monomers become connected through a covalent bond (**Figure 3**). This process requires an input of energy from the cell to be accomplished. Hydrolysis (water splitting) breaks monomers apart by doing the exact opposite. H_2O is attached to an enzyme and is broken when an $-\text{H}$ atom is connected to one monomer while the $-\text{OH}$ becomes connected to the other, breaking the covalent bond that holds the monomers together.

dehydration synthesis
an enzymatic reaction that connects two monomers while creating a water molecule

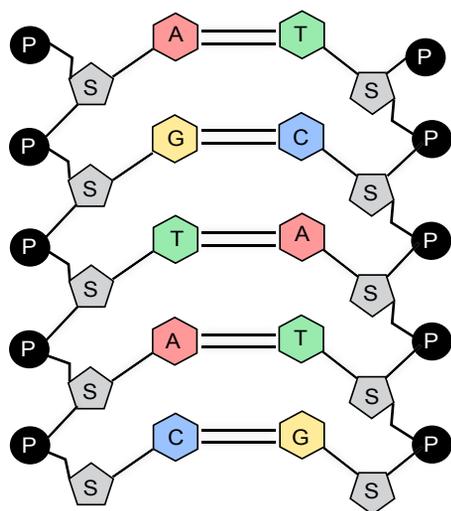


Figure 4. A DNA nucleotide is made of a five-carbon sugar ring, a phosphate group, and a nitrogen base. Nucleotides are joined together where the phosphate group binds to the fifth carbon of the sugar ring.

DNA and RNA are important macromolecules.

The double-helix macromolecule DNA contains the genetic information necessary to guide construction of all the proteins in a cell and thus allow the continuity of life. As discussed previously, DNA's single-stranded counterpart, RNA, comes in three forms, each with a specific function that aids protein synthesis. Messenger RNA (mRNA) transports the information from DNA to the ribosomes. At the ribosomes, **tRNA** transfers the genetic information into a sequence of proteins, and **rRNA** serves as the building block of ribosomes. These various DNA and RNA polymers are generally referred to as polynucleotides.

The structure of DNA and RNA determines their function.

The nucleic acids DNA and RNA have many chemical and structural similarities but can function differently based on the nucleotide monomers from which they are constructed. DNA monomers are called DNA nucleotides, and RNA monomers are called RNA nucleotides. Both types of nucleotides contain a five-carbon sugar ring, a phosphate group, and a nitrogen-containing base (**Figure 4**). The nitrogen-containing base connects to the first carbon of the sugar ring, and the phosphate attaches to the fifth carbon of the sugar ring. These nucleotide monomers link together by forming covalent bonds, which form a repeating sugar-phosphate backbone with the sugar ring of one nucleotide attached to the phosphate of the next.

There are some subtle but important differences between the structures of DNA and RNA (**Figure 5**). One difference is in the five-carbon sugar rings. The sugar in DNA nucleotides, deoxyribose, lacks an extra –OH functional group that the sugar in RNA, ribose, contains. This extra functional group prevents RNA from forming the stable double-helix structure of DNA.

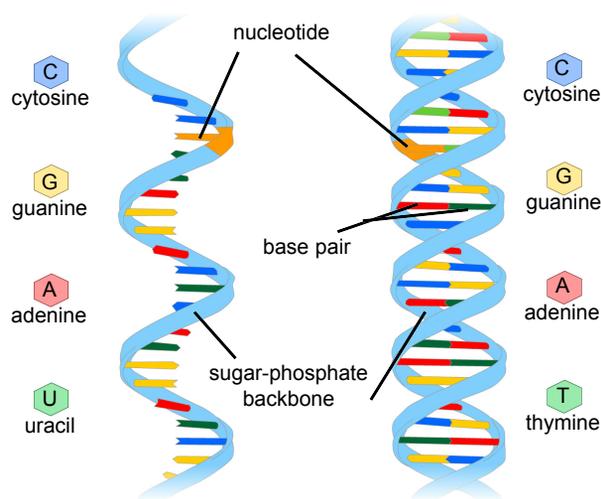


Figure 5. RNA and DNA are both nucleic acids made of nucleotides. RNA is a single strand, and DNA is a double strand. RNA contains uracil instead of thymine, which is found in DNA.

tRNA transfer RNA: a type of RNA molecule that carries amino acids to the site of protein synthesis in ribosomes

rRNA ribosomal RNA: a type of RNA molecule that makes up the main part of the structure of a ribosome

The nitrogen-containing bases are also slightly different in DNA and RNA. DNA contains cytosine, guanine, adenine, and thymine. In RNA, the base thymine is replaced with uracil. These bases pair with each other to form the rungs of the stepladder within the double helix. Cytosine and guanine are capable of pairing with each other while adenine and thymine pair with each other. In RNA, adenine pairs with uracil. The variation in the sequence of these bases is the code for the genetic information that DNA contains. Based on the different monomer types that are used to construct them, DNA and RNA are capable of performing very different functions.

Proteins are macromolecules that have many functions in the cell.

Proteins play a significant role in biology: protein makes up over 50% of the mass of the typical cell, not counting water. Proteins carry out many functions within cells including structural support, molecular transportation, and cell-to-cell communication. Chemical processes are accelerated by specialized proteins called enzymes, which are found abundantly in living systems. Although thousands of proteins have already been discovered and analyzed, many scientists, aided by continual advances in technology, continue to investigate the remaining undescribed proteins.

Amino acid monomers form proteins and determine protein function.

Protein macromolecules consist of assorted amino acid monomers that become linked together via dehydration synthesis (**Figure 6**) like beads on a necklace. A typical protein might contain about 100 linked monomers. Yet all proteins are constructed from only 20 different amino acids. As with DNA nucleotides, the order in which the pieces are put together is nearly limitless. Forming different proteins using only 20 amino acids is comparable to forming many words in a language using only 26 letters in the alphabet. Similar to the order in nucleotides, the order in which these individual amino acid monomers are joined ultimately determines the function and properties of each protein.

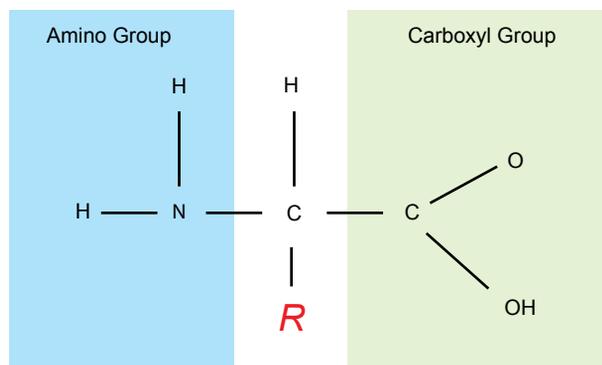


Figure 6. An amino acid consists of an amino group, a hydrogen atom, a carboxyl group, and the variable R group.

1

SELF-CHECK

How are monomers capable of interacting in such a way that allows dehydration synthesis or hydrolysis reactions to occur?

Amino acids are composed of a central carbon atom connected on four sides by a carboxyl group, an amino group, a hydrogen atom, and a variable group referred to as the R group. It is the R group that differs from amino acid to amino acid, making each one chemically unique and providing each one with specific chemical properties.

When two amino acids are joined together during a dehydration reaction, they form a **peptide bond** wherein the amino group from one amino acid joins with the carboxyl group of the other amino acid (**Figure 7**). A special enzyme helps form a peptide bond by facilitating the dehydration synthesis process that removes a water molecule and connects the monomers together.

Protein monomers interact chemically with one another.

Amino acids can be classified based on the type of R group they possess. **Non-polar** R groups are composed of a chemical structure that repels polar molecules such as water. **Polar** R groups do just the opposite, chemically attracting other polar groups, including water. When the polar and non-polar R groups of different amino acids interact with each other, the result may be a hydrophobic or hydrophilic interaction. In hydrophobic interactions, the non-polar groups interact by clustering together on the inside of the protein away from the water on the outside. In hydrophilic interactions the polar R groups interact so that they face outwards where they are exposed to water. A helpful way to remember this is to know that hydrophobic means “water fearing,” so these molecules are insoluble in water, and hydrophilic means “water loving,” so these molecules are soluble in water. These interactions occur primarily because polar molecules can hydrogen bond with each other but they cannot hydrogen bond with non-polar molecules.

In addition to hydrophobic and hydrophilic interactions, amino acids can interact in other ways. Ionic bonds can form between charged atoms (anions and cations) in different molecules. A Polar bond is a type of covalent bond that does not share the electrons equally between the two atoms because one is more electronegative than the other. Van der Waals interactions occur when positive and negative charged areas of molecules get close to each other until they weakly stick to one another. When two R groups containing sulfhydryl groups (–SH) approach each other in a folded protein (these are found on cysteine monomers), they will form a disulfide bridge with the two sulfur atoms forming a bond.

Proteins can obtain four different configurations depending on how the monomers interact chemically with one another.

A protein contains numerous amino acids held together by peptide bonds in a unique sequence known as its primary structure (**Figure 8**). The primary structure can become folded, however, as hydrogen bonds form between the carbon and nitrogen elements of the polypeptide backbone, forming what is known as the secondary structure of the protein. This secondary structure may take the conformation of either an α helix (alpha helix), a coiled or spiral shape, or a β pleated (beta pleated) sheet, resembling rows of monomers folded back on each other.

peptide bond a chemical bond connecting two amino acids with the carboxyl group of one and the amino group of the other

non-polar molecule a molecule that lacks a dipole or permanent positive and negative areas

polar molecule a molecule in which there are positive and negative areas

2

SELF-CHECK

How do DNA nucleotides and RNA nucleotides differ from one another?

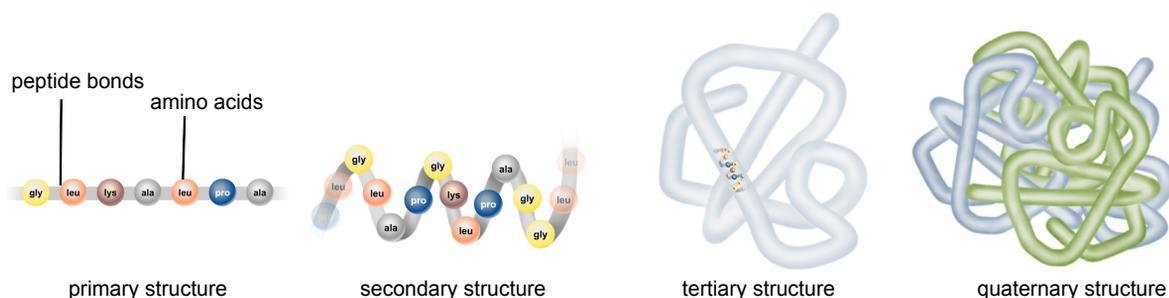


Figure 8. Proteins are made of amino acids connected by peptide bonds. These polypeptide chains can fold to form the complex three-dimensional structure of a protein.

All of the previously described chemical-bonding interactions occur between the R groups of the various amino acids in a protein and the environment where the interaction occurs. Thus, proteins can spontaneously arrange themselves into a unique three-dimensional configuration called the tertiary structure. Although the bonds that form to create these three-dimensional configurations are weak, they can stabilize the structure enough so that it remains folded.

More than one polypeptide chain in a functioning protein cause interactions that form the quaternary structure. Most functional proteins exist in this form. Similar chemical interactions involving the R groups and the environment occur in both the quaternary structure and the tertiary structure.

A protein's environment interacts chemically with protein monomers and can affect protein structure.

Just as protein monomers can interact with each other chemically, resulting in changes of conformation, they can also interact with molecules in their surrounding environment. In fact, it is possible to change the environment of a protein to change the structure of a protein. Altering the pH, salt concentration, or temperature of the environment can result in denaturation, a change of conformation that causes function loss that may or may not be reversible. When an egg is placed in a hot frying pan, the heat causes denaturation of the proteins, resulting in a cooked egg. Because this denaturation disturbs the primary structure of the protein, it is not possible for the proteins in a cooked egg to revert back to their uncooked form. However, if the primary structure is undisturbed, it is possible to return a protein to its functional shape. This is commonly done in the laboratory by removing the denaturing agent from a test-tube solution. For example, the pH can be changed back to what it was originally, allowing the protein monomers to reform their chemical bonds with each other and to re-fold.

The unique shape of each protein results in a unique function.

The function of each protein is determined by its structure. It is through the primary structure of a protein that the final tertiary or quaternary structure takes shape and becomes a functional protein. The final shape of a protein allows it to interact with other proteins and molecules as required in cell processes, much as a key and a lock interact. One protein will function in a certain capacity and incur particular results that another

protein is not able to incur, facilitated by its structure. Though this concept may seem straightforward in a textbook, for scientists trying to make sense of the thousands of proteins interacting with molecules in cells throughout an organism, discovering how these interactions occur in real life is an intense, ongoing, and often puzzling task.

Macromolecules have directionality.

Nucleic acids and proteins share a characteristic, directionality, which affects how other molecules interact with them. Directionality exists when each end of the molecule is different from the other. This characteristic of some macromolecules can affect how they function and how other molecules interact with them.

The directionality of nucleic acids affects their function.

In DNA and RNA, one end has a sugar molecule while the other has a phosphate part. The sugar end and phosphate end have specific names derived from the carbon number they are attached to. In the sugar-phosphate backbone, the end with a phosphate group attached to it is known as the 5' (five prime) end, while the one with the sugar is known as the 3' end (**Figure 9**). The nitrogenous bases branch off from an end where they may pair with their complementary bases on another nucleic acid that runs antiparallel to the first nucleic acid—its 5' to 3' backbone is going in the opposite direction, the same way the traffic on each side of a two-way street moves in opposite directions. For example, if the sequence on one strand of DNA was coded 5'AGTAC to 3', its antiparallel strand that comprises the complementary half of the double-helix would read 3'TCATG to 5'.

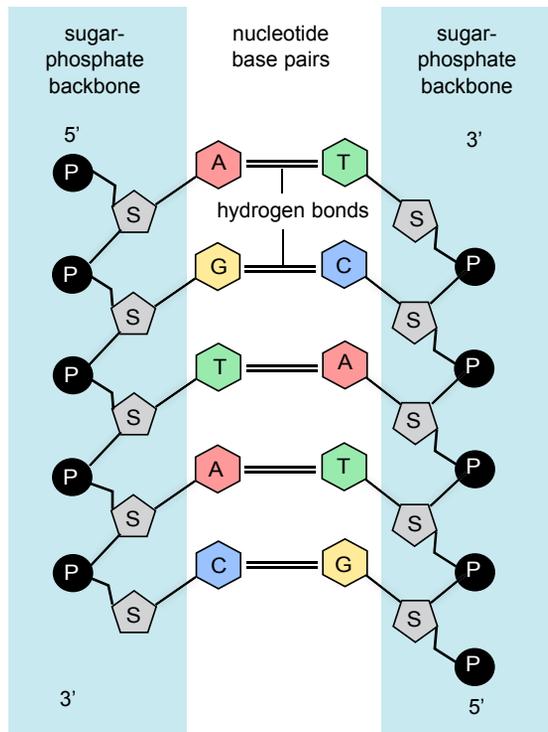


Figure 9. DNA replication takes place in a 5' to 3' direction. The leading strand is constructed continuously while the lagging strand is constructed in short segments known as Okazaki fragments. These fragments are then connected to form a continuous strand of DNA.

3

SELF-CHECK

What environmental factors might affect a protein's function?

During DNA replication, directionality impacts how the new DNA strands are put together. Elongation must take place in a 5' to 3' direction. Therefore, the DNA polymerase moving down the 3' to 5' parental DNA strand has no problem following the rule for elongation directionality when the new leading strand of DNA is constructed. For the polymerase working on the 5' to 3' parental strand, however, it is necessary to construct this new lagging strand of DNA in short segments between 1,000 and 2,000 nucleotides long. These short segments of unconnected DNA are known as Okazaki fragments until they are effectually stitched together by the enzyme DNA ligase. During the transcription process, RNA is compiled from its 5' end to its 3' end. The RNA polymerase moves downstream along the DNA gene it is transcribing in a 3' to 5' direction. Directionality also affects the function of RNA during the translation process. The ribosome attaches to the 5' end of mRNA as guided by the presence of a 5' cap and poly(A) tail on the 3' end. Because of this attachment, tRNA can assemble the correct protein sequences using the three nucleotide-wide codons.

The directionality of proteins affects their function.

Proteins also utilize directionality: one end is always a carboxyl group while the other is an amino group. There are enzymes in our bodies that only work on one end or the other of a polypeptide. This is the case with some digestive enzymes.

Extensions

- Locate and read a few current event articles or watch a few videos about genetic engineering. How might advances in the field of genetic engineering affect you now and in the future?
- Find out how genetic testing is conducted. What are some ethical pros and cons to using this technology?
- Explore genetic diseases. What are some explanations for why there are so many different genetic diseases?

Summary

Macromolecules are the building blocks of all living things. Similarly, monomers are the building blocks of macromolecules. Polymers are constructed and destructed through chemical reactions utilizing enzymes, water, and monomers. DNA and RNA nucleotides join to form the “backbone” and “stepladder” features of DNA and RNA. Functional groups are important aspects of monomer structure that allow for different chemical bonds to form between molecules. Proteins in particular are affected by chemical bonding because these bonds cause them to reshape into secondary, tertiary, and quaternary structures. Environmental variables can interfere with these chemical bonds and cause proteins to denature. Some macromolecules, including DNA, RNA, and proteins, are affected by directionality, which also impacts how they are able to function.

4

SELF-CHECK

What are some implications of directionality in DNA and RNA function?

Connections

Since all it takes to wreak havoc in an orderly biological system is to replace one monomer for another in a protein's primary sequence, it seems systems would be disordered more often. But only one in ten billion DNA nucleotides gets through the system to cause problems. How is it possible, when thousands of proteins are produced in the human body, for things not to go wrong more often? The answer lies partially in a built-in safety check that occurs during the DNA replication process itself. DNA polymerase, the same enzyme that puts nucleotide bases in place to begin with, double-checks its work as it goes. Any mistake that gets through this process has a second chance to be corrected through mismatch repair, a process that involves a special enzyme to fix wrongly placed nucleotides in a completed sequence. Thanks to these two processes, the chance of something going wrong during protein synthesis is greatly reduced, while the chances of producing a fully functional organism are increased substantially.

SELF-CHECK ANSWERS

1. Monomers can interact in dehydration synthesis and hydration reactions because enzymes facilitate these interactions.
2. Compared to DNA, the sugar in RNA contains an extra $-OH$ functional group, and the base thymine is replaced with uracil in RNA nucleotides.
3. Temperature, pH, and salt concentration are three factors that may interfere with protein function.
4. Because of directionality, a leading strand and a lagging strand are necessary during DNA replication, and special tags are necessary during translation to guide the ribosome to the correct binding location.

Unit 7 Lesson 1

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