Specific Expectations

In this chapter, you will learn how to . . .

- B1.1 analyze technological applications related to enzyme activity in the food and pharmaceutical industries (1.3)

- B2.1 use appropriate terminology related to biochemistry (1.1, 1.2, 1.3)

- B2.3 construct and draw three-dimensional molecular models of important biochemical compounds, including carbohydrates, proteins, lipids, and nucleic acids (1.2, 1.3)

- B2.4 conduct biological tests to identify biochemical compounds found in various food samples, and compare the biochemical compounds found in each food to those found in the others (1.2)

- B2.5 plan and conduct an investigation related to a cellular process, using appropriate laboratory equipment and techniques, and report the results in an appropriate format (1.3)

- B3.2 describe the structure of important biochemical compounds, including carbohydrates, proteins, lipids, and nucleic acids, and explain their function within cells (1.2)

- B3.3 identify common functional groups within biological molecules, and explain how they contribute to the function of each molecule (1.2)

- B3.4 describe the chemical structures and mechanisms of various enzymes (1.3)

- B3.5 identify and describe the four main types of biochemical reactions (1.3)

Geckos are small lizards that appear to defy gravity by running up walls and upside down on ceilings as smooth as glass—even on glass itself. Only recently, in 2002, were scientists able to explain this ability. Each gecko toe has about two million densely packed, hair-like structures called setae, and each individual seta is as long as twice the diameter of a human hair. In addition, each seta splits into hundreds of even finer tips, resulting in extremely close contact between the microscopic structures of the feet and any surface. About one million setae—a fraction of the total number a gecko has—could fit onto the surface of a dime, with an adhesive force large enough to lift a 20 kg child! All this is possible due to forces of molecular attraction operating at extremely short distances between the molecules that make up setae and the molecules that make up walls, ceilings, and other surfaces.
Launch Activity

On the Matter of Gecko Feet

Science is a system for developing knowledge by asking questions and designing ways to answer them. This knowledge does not exist in a vacuum, however. Knowledge cannot be divorced from ways in which people choose to use it. Similarly, knowledge and its application cannot be divorced from possible effects—intended or unintended—on people as well as on the environment. In other words, science, technology, society, and the environment are inseparably linked. In this activity, you will consider this linkage.

Procedure

1. Imagine you are a biologist interested in investigating geckos and their remarkable climbing abilities.
   a. On your own, write two questions that would enable you to begin developing knowledge about geckos and their feet.
   b. Share your questions with a partner, and together write two more questions.
   c. Share your additional questions with another pair of students, and together write at least two more questions.

2. Working the same way as in question 1, identify practical problems for which an understanding of gecko feet could provide a solution. For example, an understanding of gecko feet could lead to the invention of picture frames that can be hung on walls without leaving nail holes or sticky glue residue.

3. Still working as in question 1, identify possible societal and environmental consequences—both intended and unintended—of the solutions from question 2.

Questions

1. Do scientists have any responsibility for how the knowledge they develop might be used by others? Why or why not?
2. Do people who apply scientific knowledge to create solutions to practical problems have any responsibility for how they (or others) use their solutions? Why or why not?
3. Do members of society have any responsibility for the way they use scientific knowledge and technological solutions? Why or why not?
All matter is composed of elements—substances that cannot be broken down into simpler substances by ordinary chemical methods. Only about 92 naturally occurring elements serve as the building blocks of matter, including the matter that comprises you and the millions of species of organisms in the world around you. And yet only six elements—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur—are the chemical foundation for this great diversity of life. Carbon and hydrogen form the underlying structures of biological molecules, with the other four elements providing particular properties to these molecules.

The smallest particle of an element that retains the properties of that element is an atom. Each atom has its own specific atomic mass, which is the sum of its protons and neutrons. While all atoms of an element have the same number of protons, the number of neutrons can vary. Isotopes are atoms of the same element that differ in the number of their neutrons. For example, carbon has three common isotopes: carbon-12 has six neutrons (the most abundant form), carbon-13 has seven neutrons, and carbon-14 has eight neutrons. Some isotopes are unstable, which means that their nucleus decays (breaks down) by emitting radiation in the form of subatomic particles or electromagnetic waves. Unstable isotopes are radioactive and are referred to as radioisotopes. Carbon-14 is an example. Radioisotopes are valuable diagnostic tools in medicine. Using a method called radioisotope tracing doctors can inject radioactive material into a patient and trace its movement in the body. For example, cancerous tissues in the body are characterized by a much higher level of activity than healthy tissues. Consequently, cancerous cells take in more glucose—a common cellular energy source—than healthy cells. Injecting a patient with radioactive glucose and then performing a positron emission tomography (PET) scan, such as the one shown in Figure 1.1, is one method to diagnose a cancerous tumour.

Figure 1.1 This positron emission tomography (PET) scan is of a 62-year-old man’s brain. The yellow and orange area represents a tumour, which breaks down the injected radioactive glucose at a faster rate than normal cells do.

**Studying the Interactions of Molecules**

For most biological studies, chemical elements are not considered in the form of individual atoms but, rather, as components of molecules. Recall that a molecule is composed of two or more atoms and is the smallest unit of a substance that retains the chemical and physical properties of the substance. Many of the molecules of life are organic molecules. Organic molecules are carbon-based, and the carbon atoms are usually bonded to each other and to hydrogen. Many organic molecules also include atoms of nitrogen, oxygen, phosphorus, and/or sulfur.

There are major classes of biologically important organic molecules that are the cornerstones of most research in biochemistry. Biochemistry is often viewed as a field of study that forms a bridge between chemistry (the study of the properties and interactions of atoms and molecules) and biology (the study of the properties and interactions of cells and organisms). Biochemists are concerned mainly with understanding the properties and interactions of biologically important molecules. Understanding the physical and chemical principles that determine the properties of these molecules is essential to understanding their functions in the cell and in other living systems.
Interactions within Molecules

The forces that hold atoms together within a molecule are intramolecular forces (“intra” meaning within). These forces are what are generally thought of as the chemical bonds within a molecule. Bonds within molecules are covalent bonds. A covalent bond forms when the electron shells of two non-metal atoms overlap so that valence electrons of each atom are shared between both atoms. Each atom has access to the electrons in the bond, as well as to its other valence electrons. In this way, both atoms obtain a full valence shell. To illustrate this, a molecule of water, H₂O, is shown in Figure 1.2A.

Some atoms attract electrons much more strongly than other atoms. This property is referred to as an atom’s electronegativity. Oxygen, O, nitrogen, N, and chlorine, Cl, are atoms with high electronegativity. Hydrogen, H, carbon, C, and phosphorus, P, are examples of atoms with lower electronegativity. When two atoms with significantly different electronegativities share electrons in a covalent bond, the electrons are more attracted to the atom with the higher electronegativity, so they are more likely to be found near it. Because electrons have a negative charge, this causes that atom to assume a slightly negative charge, called a partial negative charge (δ–). The atom with lower electronegativity assumes a partial positive charge (δ⁺). This unequal sharing of electrons in a covalent bond creates a polar covalent bond. Figure 1.2B shows how a water molecule contains two polar covalent O–H bonds. The electrons in each bond are more strongly attracted to the oxygen atom than to the hydrogen atom and are more likely to be found near the oxygen atom. This results in the oxygen atom being partially negative and the hydrogen atoms being partially positive. Molecules such as water, which have regions of partial negative and partial positive charge, are referred to as polar molecules.

When covalent bonds are formed between atoms that have similar electronegativities, the electrons are shared fairly equally between the atoms. Therefore, these bonds are considered non-polar. If this type of bond predominates in a molecule, the molecule is considered a non-polar molecule. For example, bonds between carbon and hydrogen atoms are considered non-polar, because carbon and hydrogen have similar electronegativities. As you will see in this unit, the polarity of biological molecules greatly affects their behaviour and functions in a cell.

Figure 1.2 As shown in the electron model (A), two hydrogen atoms each share a pair of electrons with oxygen to form covalent bonds in a molecule of water, H₂O. Because oxygen is more electronegative than hydrogen, there is a partial negative charge on the oxygen and a partial positive charge on each hydrogen, as shown in the space-filling model (B).

**Predict** how two water molecules might interact, based on this diagram.
Interactions between Molecules

In addition to forces within molecules, there are also forces between molecules. These intermolecular forces (“inter” meaning between) may form between different molecules or between different parts of the same molecule if that molecule is very large. Intermolecular interactions are much weaker than intramolecular interactions. They determine how molecules interact with each other and with different molecules, and therefore they play a vital role in biological systems. Most often, intermolecular interactions are attractive forces, making molecules associate together. However, because they are relatively weak, intermolecular forces can be broken fairly easily if sufficient energy is supplied. As a result, intermolecular forces are responsible for many of the physical properties of substances. Two types of intermolecular interactions are particularly important for biological systems: hydrogen bonding and hydrophobic interactions.

Hydrogen Bonding

With its two polar O–H bonds, a water molecule is a polar molecule, with a slightly positive end and a slightly negative end. The slightly positive hydrogen atoms of one molecule of water are attracted to the slightly negative oxygen atoms of other water molecules. This type of intermolecular attraction is called a hydrogen bond, and it is weaker than an ionic or covalent bond. As shown in Figure 1.3, a hydrogen bond is represented by a dotted line to distinguish it from the stronger covalent bond. Many biological molecules have polar covalent bonds involving a hydrogen atom and an oxygen or nitrogen atom.

A hydrogen bond can occur between different molecules as well as within the same molecule. Since the cell is an aqueous environment, hydrogen bonding between biological molecules and water is very important. Although a hydrogen bond is more easily broken than a covalent bond, many hydrogen bonds added together can be very strong. Hydrogen bonds between molecules in cells help maintain the proper structure and function of the molecule. For example, the three-dimensional shape of DNA, which stores an organism’s genetic information, is maintained by numerous hydrogen bonds. The breaking and reforming of these bonds plays an important role in how DNA functions in the cell.

![Figure 1.3](image-url)

**Figure 1.3** In water, hydrogen bonds (dotted lines) form between the partially positive hydrogen atoms of one molecule and the partially negative oxygen atoms on other molecules.
**Hydrophobic Interactions**

Non-polar molecules such as cooking oil and motor oil do not form hydrogen bonds. When non-polar molecules interact with polar molecules, the non-polar molecules have a natural tendency to clump together, rather than to mix with the polar molecules, as shown in Figure 1.4. (Think of the saying, “oil and water don’t mix.”) If the molecules had human emotions and motivations, it would appear as if the non-polar molecules were drawing or shying away from the polar molecules. Thus, in their interactions with water molecules, non-polar molecules are said to be **hydrophobic** (literally meaning “water-fearing”). Polar molecules, on the other hand, have a natural tendency to form hydrogen bonds with water and are said to be **hydrophilic** (literally meaning “water-loving”).

The natural clumping together of non-polar molecules in water is referred to as the **hydrophobic effect**. As you will see in this unit, the hydrophobic effect plays a central role in how cell membranes form and helps to determine the three-dimensional shape of biological molecules such as proteins.

**Ions in Biological Systems**

An atom can obtain a stable valence shell by losing or gaining electrons rather than sharing them. For example, the sodium atom, Na, has only one electron in its outer valence shell. Once this electron is given up, the electron shell closer to the sodium nucleus, which already contains eight electrons, becomes the valence shell. When an atom or group of atoms gains or loses electrons, it acquires an electric charge and becomes an **ion**. When an atom or group of atoms loses electrons, the resulting ion is positive and is called a **cation**. When an atom or group of atoms gains electrons, the resulting ion is negative and is called an **anion**. Ions can be composed of only one element, such as the sodium ion, Na⁺, or of several elements, such as the bicarbonate ion, HCO₃⁻.

Ions are an important part of living systems. For example, hydrogen ions, H⁺, are critical to many biological processes, including cellular respiration. Sodium ions, Na⁺, are part of transport mechanisms that enable specific molecules to enter cells. For biological processes in the cell, substances that form ions, such as sodium, are almost never considered in the form of **ionic compounds**, such as sodium chloride, NaCl(s). Since the cell is an aqueous environment, almost all ions are considered as free, or dissociated ions (Na⁺(aq) and Cl⁻(aq)) since they dissolve in water.

**Learning Check**

1. What is the relationship between elements and atoms?
2. Explain, with reference to subatomic particles and stability, the difference between carbon-12 and carbon-14.
3. Explain how a polar covalent bond is different from an ionic bond.
4. Use a water molecule to describe the relationships among all the following: polar and non-polar molecules, intramolecular and intermolecular forces, hydrophilic and hydrophobic interactions.
5. What is the hydrophobic effect?
6. Biochemistry is one of the many scientific disciplines that bridge the knowledge and understanding of one field of science with another. Identify at least two other “bridging” scientific disciplines, and explain how the knowledge and understanding of one field complements the knowledge and understanding of the other in each case.
Functional Groups Determine the Properties of a Molecule

Organic molecules that are made up of only carbon and hydrogen atoms are called hydrocarbons. Hydrocarbons share similar properties—for example, they are non-polar, do not dissolve in water, have relatively low boiling points (depending on size), and are flammable. The covalent bonds between carbon and carbon and between carbon and hydrogen are "energy-rich"; breaking of the bonds releases a great deal of energy. Therefore, hydrocarbons make good fuels. Most of the hydrocarbons you encounter in everyday life, such as acetylene, propane, butane, and octane, are fuels.

Although hydrocarbons share similar properties, other organic molecules have a wide variety of properties. This is because most organic molecules also have other atoms or groups of other atoms attached to their central carbon-based structure. A cluster of atoms that always behaves in a certain way is called a functional group. Functional groups contain atoms such as oxygen (O), nitrogen (N), phosphorus (P), or sulfur (S). Certain chemical properties are always associated with certain functional groups. These functional groups provide the molecules to which they are bonded with those same chemical properties. Table 1.1 lists the common functional groups of biologically important molecules. For example, the presence of hydroxyl or carbonyl groups on a molecule makes the molecule polar. Also, a carboxyl functional group on a molecule will make it acidic, meaning it will easily release or donate a hydrogen atom to another molecule. Many of these functional groups, and therefore the molecules that contain them, can also participate in hydrogen bonding.

<table>
<thead>
<tr>
<th>Functional Group</th>
<th>Properties</th>
<th>Structural Formula</th>
<th>Example</th>
<th>Found In</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydroxyl</td>
<td>polar</td>
<td>—OH</td>
<td>Ethanol</td>
<td>carbohydrates, proteins, nucleic acids, lipids</td>
</tr>
<tr>
<td>Carbonyl</td>
<td>polar</td>
<td>—C=O</td>
<td>Acetaldehyde</td>
<td>carbohydrates, nucleic acids</td>
</tr>
<tr>
<td>Carboxyl</td>
<td>polar, acidic (donates a proton)</td>
<td>—COOH</td>
<td>Acetic acid</td>
<td>proteins, lipids</td>
</tr>
<tr>
<td>Amino</td>
<td>polar, basic (accepts a proton)</td>
<td>—NH₂</td>
<td>Alanine</td>
<td>proteins, nucleic acids</td>
</tr>
<tr>
<td>Sulphydryl</td>
<td>slightly polar</td>
<td>—S—H</td>
<td>Protein</td>
<td>proteins</td>
</tr>
<tr>
<td>Phosphate</td>
<td>polar, negatively charged</td>
<td>—PO₄³⁻</td>
<td>Glycerol phosphate</td>
<td>nucleic acids</td>
</tr>
</tbody>
</table>

Table 1.1 Important Functional Groups on Biological Molecules
Structures and Shapes of Molecules

A molecular formula shows the number of each type of atom in an element or compound. Examples of molecular formulas include H₂O, C₃H₇NO₂, and C₆H₁₂O₆. Molecular formulas are useful because they show the number and type of atoms in a molecule. Structural formulas show how the different atoms of a molecule are bonded together. When representing molecules using a structural formula, a line is drawn between atoms to indicate a covalent bond. A single line indicates a single covalent bond, double lines indicate a double bond, and triple lines indicate a triple bond. Figure 1.5 shows some examples of structural formulas. Also shown are simplified diagrams of structures that you will often see when they are written out for biological molecules. In these simplified structures, carbon atoms are sometimes indicated by a bend in a line, so their symbol, C, is not included. Also, hydrogen atoms attached to these carbon atoms are omitted but are assumed to be present.

Figure 1.5 Structural formulas show how each atom is bonded together in a molecule. Biological molecules are often drawn using a simplified form, where the intersection of two lines represents a carbon atom and any hydrogen atoms bonded to that carbon are omitted.

Identify the polar and non-polar molecules.

Structural formulas are two-dimensional representations of molecules and the bonds between molecules. However, molecules are not flat—they take up space in three dimensions. In fact, the three-dimensional shape of a molecule influences its behaviour and function. As shown in Figure 1.6, a molecule such as methane, CH₄, has a tetrahedral shape. Because they are negatively charged, the electron pairs in covalent bonds repel each other, and move as far apart as possible. If there are four bonds, as in methane, then a tetrahedral shape represents the farthest the electrons in these bonds can be from each other. Depending on the atoms and types of bonds in a molecule, different shapes are possible. Therefore, you will often see large biologically important molecules represented using three-dimensional models, such as space-filling models.

Figure 1.6 Methane (A) has four bonds and a particular three-dimensional shape, called tetrahedral. In larger biological molecules such as glucose (B), the three-dimensional shape plays a role in the molecule’s biological activity. Note that in space-filling models like the ones shown here, each atom is assigned a particular colour by convention. Carbon is black, hydrogen is white, and oxygen is red.
Activity 1.1  Molecular Shapes

In this activity, you will investigate the shapes of the molecules that result when each of carbon, hydrogen, nitrogen, and oxygen form covalent bonds.

Materials
- molecular model kit or other model building supplies

Procedure
1. Copy the following table.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Number and Type of Bond</th>
<th>Structural Formula</th>
<th>Three-Dimensional Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>methane (CH₄)</td>
<td>four single bonds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ammonia (NH₃)</td>
<td>three single bonds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>water (H₂O)</td>
<td>two single bonds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>formaldehyde (CH₂O)</td>
<td>one double bond, two single bonds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ethene (C₂H₄)</td>
<td>one double bond, four single bonds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>propadiene (C₃H₆)</td>
<td>two double bonds, four single bonds</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Write the structural formula for the first compound.

3. Using a molecular model kit, or other model-building supplies provided by your teacher, build the first molecule.

4. Draw a three-dimensional diagram for your model using the following method:
   1. Position the model so that as many atoms as possible are in the same plane—that is, so the atoms lie within the same flat surface.
   2. Draw circles to represent each atom.
   3. Use solid lines to represent bonds between atoms that lie in the same plane as the surface of the paper you are drawing on.
   4. Use dashed lines to represent bonds between atoms that are directed away from you, into the plane of the paper.
   5. Use wedged lines to represent bonds between atoms that are directed toward you, out of the plane of the paper.

5. Repeat steps 2, 3, and 4 for the remaining compounds.

Questions
1. Describe the shape of the molecule when an atom forms each of the following:
   a. four single bonds
   b. three single bonds
   c. two single bonds
   d. one double bond, and two single bonds
   e. one double bond, and four single bonds
   f. two double bonds, and four single bonds

2. Predict the shape of phosphine, PH₃.

3. Phosphorus and sulfur are important elements in biological molecules. Given that phosphorus is in the same chemical family as nitrogen and sulfur is in the same chemical family as oxygen, predict the shapes formed when phosphorus and sulfur form covalent bonds.

Bohr-Rutherford diagrams of phosphorus, P, (left) and sulfur, S, (right).
Section 1.1 Review

Review Questions

1. **K/U** Name the four most common elements that make up living systems.

2. **A**
   a. Describe how radioisotopes can be used to locate cancerous tissues in the body.
   b. How might a biologist use the process of radioisotope tracing to study digestion? What type of information could the biologist hope to learn from this investigation?

3. **C** Use a concept map to show the connections between the following terms: atom, functional group, isotope, molecule, radioisotope, organic molecule, and ion.

4. **A** Give one example of an intramolecular force, and one example of an intermolecular force. Which type of force is stronger? Use logical reasoning to explain how you know this must be so in order for life to exist.

5. **C** Sketch a structural diagram of a water molecule. Label the covalent bonds, the atoms, and the polarity of each part of the molecule.

6. **T/I** Identify each of the following bonds as polar or non-polar. Provide justification for your answer.
   a. O–O
   b. H–N
   c. C–Cl
   d. P–O

7. **A** Fluorine is never observed in naturally-occurring biological compounds. Since fluorine has a high electronegativity, predict the type of bond that fluorine would likely form with carbon.

8. **K/U** Three students discussed the properties of a water molecule. Ari said, “Water’s polarity and water’s ability to form hydrogen bonds are actually the same thing. Any polar molecule can form hydrogen bonds with any another polar molecule.” Jordan said, “Water’s polarity and water’s ability to form hydrogen bonds are connected, but they are not the same thing. Some polar molecules cannot form hydrogen bonds, and others, like water, can.” Ravi said, “Water’s polarity and water’s ability to form hydrogen bonds have nothing to do with each other. Even if water had no polar bonds, it would still be able to form hydrogen bonds.”
   Which student, if any, do you agree with? Write a paragraph explaining why.

9. **A** Hydrocarbons contain many hydrogen atoms but are not known to carry out hydrogen bonding. Explain this apparent discrepancy.

10. **C** Use a magnet analogy to explain the attractive forces between water molecules. Explain also the limitations of using a magnet analogy for this purpose.

11. **A** Use the hydrophobic effect to explain why the oil in salad dressing will rise to the top of a water-based mixture of vinegar and herbs.

12. **K/U**
   a. How does a cation differ from an atom?
   b. Provide two examples of cations that are important in biological systems.

13. **K/U** What are the advantages of using a molecular formula to depict a molecule, rather than a structural formula? What are the advantages of using a structural formula?

14. **C** Using a table or a Venn diagram, compare the two-dimensional structure of methane with the three-dimensional structure of methane.

15. **T/I** The table compares the percentage (by mass) of three elements in the human body and Earth’s crust. Explain why the values in each case are different.

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage in Body</th>
<th>Percentage in Earth’s Crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>9.5</td>
<td>0.14</td>
</tr>
<tr>
<td>Carbon</td>
<td>18</td>
<td>0.03</td>
</tr>
<tr>
<td>Oxygen</td>
<td>65</td>
<td>47</td>
</tr>
</tbody>
</table>
Many of the molecules of living organisms are composed of thousands of atoms. These molecules are considered **macromolecules**, which are large molecules that often have complex structures. Many macromolecules are **polymers**, which are long chain-like substances composed of many smaller molecules that are linked together by covalent bonds. These smaller molecules are called **monomers**, which can exist individually or as units of a polymer. The monomers in a polymer determine the properties of that polymer. As shown in **Figure 1.7**, there are four main types of biological macromolecules: carbohydrates, lipids, proteins, and nucleic acids. Some occur as polymers that are composed of characteristic monomers. This section will discuss the basic structures of these molecules, as well as some important examples and their functions in the cell.

**Figure 1.7** Carbohydrates, nucleic acids, proteins, and lipids (shown here as a triglyceride) are biologically important components of larger structures in the cell.

*Explain why the triglyceride shown here does not fit the monomer-polymer relationship that exists for the other macromolecules.*
Carbohydrates

Sugars and starches are examples of carbohydrates. Carbohydrates are a type of biological molecule that always contains carbon, hydrogen, and oxygen, nearly in the ratio of two atoms of hydrogen and one atom of oxygen for every one atom of carbon. This is why a general formula for carbohydrates is often written using the formula \((CH_2O)_n\), where \(n\) is the number of carbon atoms. Sugars and starches store energy in a way that is easily accessible by the body. Because they contain a high proportion of hydroxyl functional groups and many contain carbonyl groups, most carbohydrates are polar molecules, and many dissolve in water.

Monosaccharides and Disaccharides

If the number of carbon atoms in a carbohydrate molecule is between three and seven, the carbohydrate is classified as a simple sugar. These sugars are called monosaccharides ("mono" meaning one; "saccharide" meaning sugar) because they are composed of a single carbon-based monomer structure. Examples of common monosaccharides are shown in Figure 1.8. Glucose in the body is commonly referred to as blood sugar, because it is the sugar that cells in the body use first for energy. Fructose is often called fruit sugar, since it is a principal sugar in fruits. Galactose is a sugar found in milk. These three simple sugars all have the molecular formula \(C_6H_{12}O_6\). The exact three-dimensional shapes of their structures differ, as does the relative arrangement of the hydrogen atoms and hydroxyl groups. Molecules that have the same molecular formula but different structures are called isomers. Glucose, fructose, and galactose are isomers of each other. The different structures of these molecules results in them having very different three-dimensional shapes. These differences are enough for the molecules to be treated very differently by your body and in the cell. For example, your taste buds will detect fructose as being much sweeter than glucose, even though they have the same chemical composition.

Two monosaccharides can join to form a disaccharide. The covalent bond between monosaccharides is called a glycosidic linkage. It forms between specific hydroxyl groups on each monosaccharide. Common table sugar is the disaccharide sucrose, shown in Figure 1.9, which is composed of glucose bonded with fructose. Galactose and glucose bond to form the disaccharide lactose, which is a sugar found in milk and other dairy products. Some people are lactose-intolerant and can experience side effects such as cramping and diarrhea after consuming foods that contain lactose. These side effects result from body cells being unable to digest (break down) lactose into its monosaccharide monomers.
Polysaccharides

Monosaccharides are the monomers for carbohydrates that are more complex. Many monosaccharides can join together by glycosidic linkages to form a polysaccharide ("poly" meaning many). Three common polysaccharides are starch, glycogen, and cellulose. All three are composed of monomers of glucose. However, the different ways that the glucose units are linked together results in these molecules having quite different three-dimensional shapes. This, in turn, is reflected in them having very different functions. Plants store glucose in the form of starch, and animals store glucose in the form of glycogen. These molecules provide short-term energy storage, whereby glucose can be easily accessed from their breakdown in the cell. Starch and glycogen differ from each other in the number and type of branching side chains, represented in Figure 1.10. Because there are many more branches on the glycogen molecule, it can be broken down for energy much more rapidly than starch can.

Cellulose carries out a completely different function—it provides structural support in plant cell walls. The type of glycosidic linkage between monomers of cellulose is different from the type for starch and glycogen. The different linkages are possible because the hydroxyl group on carbon-1 of glucose can exist in two different positions. These positions are referred to as alpha and beta, as shown in Figure 1.11. The alpha form results in starch and glycogen, while the beta form results in cellulose.

Starch and glycogen are digestible by humans and most other animals because we have the enzymes that recognize this glycosidic linkage and catalyze the cleavage into glucose monomers. However, cellulose is indigestible because we lack the enzyme that recognizes the glycosidic linkage in that macromolecule.

**Figure 1.10** Starch, glycogen, and cellulose are all polymers of glucose. Starch has a three-dimensional structure that is much more linear than the highly branched structure of glycogen. Cellulose has a linear structure and has a different type of glycosidic linkage between monomers compared with the other two polysaccharides.

**polysaccharide** a carbohydrate polymer composed of many monosaccharides joined by covalent bonds between particular atoms
Like carbohydrates, lipids are composed of carbon, hydrogen, and oxygen atoms, but lipids have fewer oxygen atoms and a significantly greater proportion of carbon and hydrogen bonds. As a result, lipids are hydrophobic—they do not dissolve in water. Since the cell is an aqueous environment, the hydrophobic nature of some lipids plays a key role in determining their function.

The presence of many energy-rich C–H bonds makes lipids efficient energy-storage molecules. In fact, lipids yield more than double the energy per gram that carbohydrates do. Because lipids store energy in hydrocarbon chains, their energy is less accessible to cells than energy from carbohydrates. For this reason, lipids provide longer-term energy and are processed by the body after carbohydrate stores have been used up.

Lipids are crucial to life in many ways. For example, lipids insulate against heat loss, they form a protective cushion around major organs, and they are a major component of cell membranes. In non-human organisms, lipids provide water-repelling coatings for fur, feathers, and leaves.

**Learning Check**

7. Explain how the following terms are related: macromolecule, polymer, monomer.

8. Identify at least three structural and functional characteristics of carbohydrates.

9. Why are glucose, fructose, and galactose isomers?

10. Use a graphic organizer to describe the similarities and differences among monosaccharides, disaccharides, and polysaccharides.

11. Identify two functions of carbohydrates in living systems.

12. Describe the similarities of and differences between starch, glycogen, and cellulose.
Triglycerides: Lipids Used for Energy Storage

As shown in Figure 1.12, triglycerides are composed of one glycerol molecule and three fatty acid molecules. The bond between the hydroxyl group on a glycerol molecule and the carboxyl group on a fatty acid is called an ester linkage, because it results in the formation of an ester functional group. A fatty acid is a hydrocarbon chain that ends with an acidic carboxyl group, –COOH. Fatty acids are either saturated or unsaturated. A saturated fatty acid has no double bonds between carbon atoms, while an unsaturated fatty acid has one or more double bonds between carbon atoms. If the unsaturated fatty acid has one double bond, it is monounsaturated; unsaturated fatty acids with two or more double bonds are polyunsaturated. Humans cannot synthesize polyunsaturated fats. Therefore, these essential fats must be consumed in our diet.

As shown in Figure 1.13, the presence of double bonds in a triglyceride affects its three-dimensional shape. Naturally occurring unsaturated fats have cis double bonds, which cause the long hydrocarbon chain to bend. This alters the physical properties of the triglyceride and the behaviour of the molecule in the body. Triglycerides containing saturated fatty acids, such as lard and butter, are generally solid fats at room temperature. Triglycerides containing unsaturated fatty acids, such as olive oil or canola oil, are generally liquid oils at room temperature. A diet high in saturated fat is linked with heart disease in humans. However, some unsaturated fatty acids, particularly polyunsaturated fatty acids, are known to reduce the risk of heart disease.

A food preservation process called hydrogenation involves chemical addition of hydrogen to unsaturated fatty acids of triglycerides to produce saturated fats. A by-product of this reaction is the conversion of cis fats to trans fats, whereby remaining double bonds are converted to a trans conformation. Consumption of trans fats is associated with increased risk of heart disease.
**Phospholipids: Components of Cell Membranes**

The main components of cell membranes are **phospholipids**. As shown in Figure 1.14, the basic structure of a phospholipid is similar to that of a triglyceride. The difference is that a phosphate group replaces the third fatty acid of a triglyceride. Attached to the phosphate group is an \( R \) group, which is a group of atoms that varies in composition. It is this \( R \) group that defines the type of phospholipid. The “head” portion of a phospholipid molecule is polar, while the lower “tail” portion has only non-polar \( C—C \) and \( C—H \) bonds. Therefore, the “head” of a phospholipid molecule is hydrophilic, while the non-polar “tail” is hydrophobic.

This dual character of a phospholipid is essential to its function in living organisms. In aqueous environments, phospholipids form a **lipid bilayer**, as shown in Figure 1.15. In a phospholipid bilayer, the hydrophilic heads face the aqueous solution on either side of the bilayer. The tails form a hydrophobic interior. In addition to the interior of a cell being an aqueous environment, cells are surrounded by an aqueous extra-cellular fluid. Therefore, membranes of the cell, which are made of phospholipids, adopt this structure. In Chapter 2, you will examine the vital role of lipid bilayers in the cell.

**Figure 1.15** In water, phospholipids form a lipid bilayer. They naturally arrange themselves so that the non-polar “tails” are tucked away from the water, and the polar “heads” are directed toward the water.

**Predict** what might happen to a bilayer structure if many of the phospholipids contained unsaturated fatty acids.
Other Lipids

**Steroids** are a group of lipids that are composed of four carbon-based rings attached to each other. Each steroid differs depending on the arrangement of the atoms in the rings and the types of functional groups attached to the atoms. Cholesterol, shown in Figure 1.16, is a component of cell membranes in animals, is present in the blood of animals, and is the precursor of several other steroids, such as the sex hormones testosterone and estrogen. Testosterone regulates sexual function and aids in building bone and muscle mass. Estrogen regulates sexual function in females, and acts to increase the storage of fat. Cholesterol is made by mammals, and it can also enter the body as part of the diet. Although it performs important functions, high levels of cholesterol in blood can cause fatty material to accumulate inside the lining of blood vessels, reducing blood flow and contributing to heart disease.

In medicine, steroids are used to reduce inflammation. Examples include topical steroid ointments to treat skin conditions and inhalers to treat asthma. **Anabolic steroids** are synthetic compounds that mimic male sex hormones. Used to build muscle mass in people who have cancer and AIDS, anabolic steroids are also frequently misused by athletes and their use is banned in most competitive sports.

**Waxes** have a diversity of chemical structures, often with long carbon-based chains, and are solid at room temperature. They are produced in both plants (for example, carnauba wax) and animals (for example, ear wax, beeswax, and lanolin). In plants, waxes coat the surfaces of leaves, preventing water and solutes from escaping and helping to repel insects. Waxes are present on the skin, fur, and feathers of many animal species and on the exoskeletons of insects. The whale species shown in Figure 1.17 gets its common name from the wax-filled organ that occupies its head and represents as much as one-third of the total length of the whale and one-quarter of its total mass. Whales can generate sound from this organ, which can be used for sonar to locate prey.

**Figure 1.16** Cholesterol is a member of a large group of lipids called steroids.

**Figure 1.17** The sperm whale gets its name from the spermaceti-filled structure located at its head. Spermaceti is a liquid wax at internal body temperature, but it changes to a milky-white solid with exposure to air. The whale was once hunted for its spermaceti, which was highly prized for its use in candles and lubricant oils.
Proteins

Proteins represent an extremely diverse type of macromolecules that can be classified into groups according to their function, as outlined below. The body contains tens of thousands of different groups of proteins, and each of these groups contains thousands of specific examples.

- Catalyzing chemical reactions: There are a large group of proteins that can catalyze, or speed up, specific biological reactions.
- Providing structural support: Protein fibres provide structural support in such materials as bones, tendons, skin, hair, nails, claws, and beaks.
- Transporting substances in the body: In the blood, proteins transport small molecules such as oxygen. Proteins in cell membranes transport substances in and out of the cell.
- Enabling organisms to move: Animals move by muscle contraction, which involves the interaction of the proteins actin and myosin.
- Regulating cellular processes: Proteins such as some hormones carry signals between cells that can regulate cell activities. Proteins can also regulate the genetic activity of a cell by altering gene expression.
- Providing defence from disease: Antibodies are proteins that combat bacterial and viral infections.

How is it possible for a single type of macromolecule to carry out such diverse activities in biological systems? The functions of proteins depend on their three-dimensional structures. These structures are highly specific and all begin with the repeating units of which proteins are composed—amino acids.

Amino Acids: Monomers of Proteins

A protein is a macromolecule composed of amino acid monomers. As shown in Figure 1.18, an amino acid contains a central carbon atom that is bonded to the following four atoms or groups of atoms: a hydrogen atom, an amino group, a carboxyl group, and an $R$ group. (An $R$ group is also called a side chain.) Because all amino acids have the same underlying structure, the distinctive shape and properties of an amino acid result from its $R$ group. All amino acids are somewhat polar, due to the polar $\text{C}=$O, $\text{C}–\text{O}$, $\text{C}–\text{N}$, and $\text{N}–\text{H}$ bonds. Some amino acids are much more polar than others, depending on the polarity of the $R$ group.

13. In what ways are lipids similar to and different from carbohydrates?
14. Explain why lipids are efficient energy-storage molecules.
15. Sketch and describe the basic structure of a triglyceride, and explain how the presence of double bonds affects its properties.
16. What is meant by the dual character of a phospholipid molecule, and how is this essential to its function in living systems?
17. Identify two examples of steroids, and explain their significance.
18. What property of waxes is common in both plants and animals? Give an example and its significance in a specific plant and a specific animal.
Figure 1.19 shows the 20 common amino acids that make up most proteins. Eight of these amino acids, called essential amino acids, cannot be produced by the human body and must be consumed as part of the diet. These are isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine.

![Amino Acid Structures]

In proteins, amino acids are joined by covalent bonds called peptide bonds. As shown in Figure 1.20, a peptide bond forms between the carboxyl group on one amino acid and the amino group on another. A polymer composed of amino acid monomers is often called a polypeptide. Proteins are composed of one or more polypeptides. Amino acids can occur in any sequence in a polypeptide. Since there are 20 possible amino acids for each position, an enormous variety of proteins are possible. For example, a protein made of 50 amino acids could have $20^{50}$ different possible sequences. This number is greater than the number of atoms making up the Earth and everything on it.

**polypeptide** a polymer composed of many amino acids linked together by covalent bonds

**peptide bond**

**dipeptide**
Levels of Protein Organization

The structure of a protein can be divided into four levels of organization, which are shown in Figure 1.21. The first level, called the primary structure, is the linear sequence of amino acids. The peptide bonds linking the amino acids may be thought of as the backbone of a polypeptide chain. Since the peptide bonds are polar, hydrogen bonding is possible between the C=O of one amino acid and the N–H of another amino acid. This contributes to the next level of organization, called the secondary structure. A polypeptide can form a coil-like shape, called an α (alpha) helix, or a folded fan-like shape, called a β (beta) pleated sheet. The three-dimensional structure of proteins results from a complex process of protein folding that produces the tertiary structure. Most of the protein folding process occurs naturally as the peptide bonds and the different R groups in a polypeptide chain interact with each other and with the aqueous environment of the cell. Most of what determines tertiary structure is the hydrophobic effect. For example, polar hydrophilic groups will be directed toward the aqueous environment, while non-polar hydrophobic groups will tend to be directed toward the interior of the protein’s three-dimensional shape. There are also other stabilizing forces, such as hydrogen bonding between R groups of different amino acids and electrostatic attractions between oppositely charged R groups. Scientists now know that the process of protein folding also involves the assistance of a class of proteins called molecular chaperones. These proteins interact with the polypeptide chain and, through a series of steps, produce the final properly folded protein.

Although some proteins are composed of only one polypeptide, others are made of more than one polypeptide, each with its own primary, secondary, and tertiary structures. In proteins with multiple polypeptide chains, these separate polypeptides are arranged into a fourth level of organization, called the quaternary structure.

Under certain conditions, proteins can completely unfold in a process called denaturation. Denaturation occurs when the normal bonding between R groups is disturbed. Intermolecular bonds break, potentially affecting the secondary, tertiary, and quaternary structures. Conditions that can cause denaturation include extremes of hot and cold temperatures and exposure to certain chemicals. Once a protein loses its normal three-dimensional shape, it is no longer able to perform its usual function.
Nucleic Acids

The fourth type of biologically important molecule is a class of macromolecules called nucleic acids. The two types of nucleic acids are DNA (deoxyribonucleic acid) and RNA (ribonucleic acid). DNA contains the genetic information of an organism. This information is interpreted or decoded into particular amino acid sequences of proteins, which carry out the numerous functions in the cell. The conversion of genetic information that is stored in DNA to the amino acid sequence of proteins is carried out with the assistance of different RNA molecules. The amino acid sequence of a protein is determined by the nucleotide sequences of both DNA and RNA molecules.

DNA and RNA are polymers made of thousands of repeating nucleotide monomers. As shown in Figure 1.22, a nucleotide is made up of three components that are covalently bonded together:

- a phosphate group
- a sugar with five carbon atoms
- a nitrogen-containing base

While both DNA and RNA are composed of nucleotide monomers, the nucleotide make-up of these nucleic acids differs somewhat. The nucleotides in DNA contain the sugar deoxyribose, and the nucleotides in RNA contain the sugar ribose. This difference accounts for their respective names. There are four different types of nitrogenous bases in DNA: adenine (A), thymine (T), guanine (G), and cytosine (C). In RNA, all but one of these same bases is used. The exception is that thymine is replaced by the base uracil (U).

**Figure 1.22** Nucleotides contain a phosphate group, a five-carbon sugar, and a nitrogen-containing base. DNA nucleotides contain a deoxyribose sugar, while RNA nucleotides contain ribose as the sugar component. The base shown here is adenine.
A polymer of nucleotides is often referred to as a strand. The covalent bond between adjacent nucleotides is called a phosphodiester bond, and it occurs between the phosphate group on one nucleotide and a hydroxyl group on the sugar of the next nucleotide in the strand. A nucleic acid strand, therefore, has a backbone made up of alternating phosphates and sugars with the bases projecting to one side of the backbone, as shown in Figure 1.23. Just as amino acids in proteins have a specific order, nucleotides and their bases occur in a specific order in a strand of DNA or RNA. DNA is composed of two strands twisted about each other to form a double helix. When unwound, DNA resembles a ladder. The sides of the ladder are made of alternating phosphate and sugar molecules, and the rungs of the ladder are made up of pairs of bases held together with hydrogen bonds. Nucleotide bases always pair together in the same way. Thymine (T) base pairs with adenine (A), and guanine (G) base pairs with cytosine (C). These bases are said to be complementary to each other. RNA, on the other hand, is single-stranded. Further details of the structures and functions of DNA and RNA will be discussed in Unit 3.

The shape of a biological compound plays a significant role in the ability to carry out a particular function in the body. In this activity, you will build and draw three-dimensional models of carbohydrates, proteins, lipids, nucleic acids, and their monomers in order to better understand their structural similarities and differences.

**Materials**
- molecular model kit or other model-building supplies, or
- appropriate software package

**Procedure**
1. Choose one of the following biological molecules to build:
   - monosaccharide
   - disaccharide
   - polysaccharide
   - triglyceride
   - phospholipid
   - saturated fatty acid
   - amino acid
   - polypeptide
   - nucleotide
   - DNA
   - RNA
   - unsaturated fatty acid
2. Using a molecular model kit, model-building supplies, or an appropriate software program, construct a three-dimensional model of your biological compound.
3. Sketch a diagram for each molecule that you build.

**Questions**
1. On your diagram, identify:
   - the biological compound by its type
   - any functional groups, and provide their names
   - polarity (of the molecule, or parts of the molecule)
   - solubility in water
2. For each class of biological molecule that you built, identify a structural feature unique to that class.
3. Describe the relationship between the structural features and the function of the molecule you built.
Summary of Biologically Important Molecules

The four types of macromolecules contain mostly carbon, hydrogen, and oxygen, with varying amounts of nitrogen, phosphorus, and sulfur. The presence of certain functional groups on these molecules provides them with particular properties, such as polar groups on phospholipids, or non-polar side chains on amino acids. Functional groups, in turn, influence and determine the functions of macromolecules in the cell. Table 1.2 outlines important structural features and examples of macromolecules.

Table 1.2  Examples of Biologically Important Molecules

<table>
<thead>
<tr>
<th>Carbohydrates</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Structure</strong></td>
<td><strong>Examples</strong></td>
</tr>
<tr>
<td>Monosaccharide</td>
<td>Contains a single three- to seven-carbon atom-based structure</td>
<td>Glucose, fructose, galactose</td>
</tr>
<tr>
<td>Disaccharide</td>
<td>Contains two monosaccharides joined by a glycosidic linkage</td>
<td>Sucrose, lactose, maltose</td>
</tr>
<tr>
<td>Polysaccharide</td>
<td>Contains many monosaccharides joined by glycosidic linkages</td>
<td>Starch, glycogen, cellulose</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lipids</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Structure</strong></td>
<td><strong>Examples</strong></td>
</tr>
<tr>
<td>Triglyceride</td>
<td>Contains three fatty acids joined to glycerol by ester linkages</td>
<td>Lard, butter, vegetable oils</td>
</tr>
<tr>
<td>Phospholipid</td>
<td>Contains two fatty acids and a phosphate group joined to glycerol</td>
<td>Phosphatidylcholine</td>
</tr>
<tr>
<td>Steroid</td>
<td>Contains four carbon-based rings attached to one another</td>
<td>Cholesterol, testosterone, estrogen</td>
</tr>
<tr>
<td>Wax</td>
<td>Contains long carbon-based chains</td>
<td>Earwax, beeswax, spermaceti</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Protein</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Structure</strong></td>
<td><strong>Examples</strong></td>
</tr>
<tr>
<td>Catalyst</td>
<td>Contains amino acid monomers joined by peptide bonds</td>
<td>Amylase, sucrase</td>
</tr>
<tr>
<td>Transport</td>
<td>All have primary, secondary, tertiary structure</td>
<td>Hemoglobin, ion channel proteins</td>
</tr>
<tr>
<td>Structural</td>
<td></td>
<td>Collagen, keratin</td>
</tr>
<tr>
<td>Movement</td>
<td></td>
<td>Myosin, actin</td>
</tr>
<tr>
<td>Regulatory</td>
<td></td>
<td>Hormones, neurotransmitters</td>
</tr>
<tr>
<td>Defence</td>
<td></td>
<td>Antibodies</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nucleic Acids</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Structure</strong></td>
<td><strong>Some Functions</strong></td>
</tr>
<tr>
<td>DNA</td>
<td>Contains deoxyribonucleotide monomers (A, G, T, C)</td>
<td>Stores genetic information of an organism</td>
</tr>
<tr>
<td>RNA</td>
<td>Contains ribonucleotide monomers (A, U, G, C)</td>
<td>Participates in protein synthesis</td>
</tr>
</tbody>
</table>
Section 1.2 Review

Section Summary

- Carbohydrates can act as short-term energy-storage and structural biological molecules. They include polysaccharides, and disaccharides and monosaccharides (sugars). Polysaccharides are macromolecules composed of monosaccharide monomers.
- Lipids are longer-term energy storage and structural biological molecules that contain a higher proportion of non-polar C–C and C–H bonds than carbohydrates. Triglycerides, phospholipids, steroids, and waxes are different types of lipids.
- Proteins are macromolecules composed of amino acid monomers. Proteins have primary, secondary, tertiary, and sometimes quaternary structures, which are essential for their function. Proteins enable chemical reactions in living systems, and also perform a wide variety of structural and regulatory roles.
- Nucleic acids are macromolecules composed of nucleotide monomers. DNA and RNA are both nucleic acids. DNA stores the hereditary information of a cell. RNA plays a central role in the synthesis of proteins.

Review Questions

1. K/U A carbon atom can bond in a variety of configurations, which is one reason why carbon atoms form the backbone of all biological molecules. Look through the structural diagrams in this section, and identify at least three different shapes that carbon atoms can form when bonded to each other.

2. K/U Identify the monomer for each type of polymer.
   a. protein  
   b. glycogen  
   c. RNA

3. K/U Identify the functional group(s) on each biological molecule.
   a.  
   b.  

4. K/U Arrange the following biological molecules from smallest to largest, and give reasons for your sequence: cellulose, amino acid, ribose, triglyceride.

5. A If humans had the ability to digest cellulose, what would a high-fibre diet do to blood glucose levels?

6. K/U A sample of fat contains about twice as much energy as the same mass of carbohydrate. Compare the structures of each type of biological molecule to explain why.

7. C Use one or more labelled sketches to show the types of intermolecular and intramolecular interactions that determine the final structure of a protein.

8. K/U When placed in water, phospholipid molecules form the structures shown here. Explain why.

9. A Biologists and health science researchers continually conduct research to determine the roles of fatty acids and other macromolecules in health and longevity. Use your knowledge of biochemistry to explain how a balanced diet offsets the need to follow the latest dietary trend.

10. A Ninhydrin is a compound that is commonly used in forensic identification, because it turns purple in contact with the amino acids often found in sweat residue. Using the structure provided, answer the questions below.

   a. Determine the number of carbonyl and hydroxyl functional groups present in ninhydrin.
   b. How many carboxylic acid functional groups are present? Explain your answer.

11. A Using your understanding of protein structure and protein denaturation, infer how a hair-straightening iron works.

12. C Use a Venn diagram to compare and contrast a strand of DNA and a strand of RNA.
The chemical reactions that are associated with biological processes can be grouped into several types. Often, these biochemical reactions involve a combination of more than one type. The four main types of chemical reactions that biological molecules undergo in the cell are neutralization, oxidation-reduction, condensation, and hydrolysis reactions.

**Neutralization (Acid-Base) Reactions**

In the context of biological systems, acids and bases are discussed in terms of their behaviour in water. An **acid** can be defined as a substance that produces hydrogen ions, \( H^+ \), when it dissolves in water. Thus, acids increase the concentration of hydrogen ions in an aqueous solution. A **base** can be defined as a substance that produces hydroxide ions, \( OH^- \), when it dissolves in water, increasing the concentration of hydroxide ions. As you will see in this section, a base can also be thought of as a substance that accepts or reacts with hydrogen ions.

The **pH scale**, shown in Figure 1.24, ranks substances according to the relative concentrations of their hydrogen ions. Substances that have a pH lower than 7 are classified as acids. Substances that have a pH higher than 7 are classified as bases. Because pure water has equal concentrations of hydrogen ions and hydroxide ions, it is neither an acid nor a base. With a pH of 7, water is classified as neutral.

![Figure 1.24 Pure water has a pH of 7. Acid solutions have lower pH values, and basic solutions have higher pH values.](image)

When an acid chemically interacts with a base, they undergo a **neutralization reaction** that results in the formation of a salt (an ionic compound) and water. As a result of a neutralization reaction, the acid loses its acidic properties and the base loses its basic properties. In other words, their properties have been cancelled out, or neutralized.
Many of the chemical reactions that occur in the body can only take place within a narrow range of pH values, and illness results when pH changes beyond this range. For example, the normal pH of human blood ranges from 7.35 to 7.45. If blood pH increases to 7.5, as might happen if a person breathes too quickly at high altitudes, feels extremely anxious, or takes too many antacids, the person can feel dizzy and agitated. Such a condition is called alkalosis. On the other hand, acidosis occurs if blood pH falls to within 7.1 and 7.3. Symptoms of acidosis include disorientation and fatigue and can result from severe vomiting, brain damage, and kidney disease. Blood pH that falls below 7.0 and rises beyond 7.8 can be fatal.

To maintain optimum pH ranges, organisms rely on buffers—substances that resist changes in pH by releasing hydrogen ions when a fluid is too basic and taking up hydrogen ions when a fluid is too acidic. Most buffers exist as specific pairs of acids and bases. For example, one of the most important buffer systems in human blood involves the pairing of carbonic acid, \( \text{H}_2\text{CO}_3(\text{aq}) \), and hydrogen carbonate ion, \( \text{HCO}_3^- (\text{aq}) \). The reaction that takes place between these two substances is shown in Figure 1.25. Notice the double arrow in the reaction equations. This arrow means that the reaction can occur in both directions, which is a requirement for buffers.

**Figure 1.25** The carbonic acid–hydrogen carbonate ion buffer system is a key system in the body. If blood becomes too basic, carbon dioxide and water react to to produce carbonic acid, which dissociates into hydrogen carbonate and hydrogen ions and increases the acidity of the blood.

Explain how this buffer system works to reduce the acidity of blood.

**Oxidation-Reduction Reactions**

Another key type of chemical reaction in biochemistry is based on the transfer of electrons between molecules. When a molecule loses electrons it becomes oxidized and has undergone a process called oxidation. Electrons are highly reactive and do not exist on their own or free in the cell. Therefore, when one molecule undergoes oxidation, the reverse process must also occur to another molecule. When a molecule accepts electrons from an oxidized molecule, it becomes reduced and has undergone a process called reduction. Because oxidations and reductions occur at the same time, the whole reaction is called an oxidation-reduction reaction, which is often abbreviated to the term redox reaction.

A common type of redox reaction is a combustion reaction. For example, the combustion of propane, \( \text{C}_3\text{H}_8 \), in a gas barbecue occurs according to the following chemical equation:

\[
\text{C}_3\text{H}_8 + 5\text{O}_2 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O}
\]

The propane is oxidized, and the oxygen is reduced. This reaction also releases a large amount of energy—energy that is used to cook food on the barbecue.
Similar types of redox reactions occur in cells. For example, the process of cellular respiration has an overall chemical equation of

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Sugars such as glucose are oxidized to produce carbon dioxide and water. Note, however, that this chemical equation represents an overall reaction. As you will see in Unit 2, cellular respiration involves oxidation of glucose through a series of redox reactions. The energy released at each step in the series is stored in the form of chemical bonds of molecules that are made during the process. This allows the energy to be harnessed by the cell in discrete steps, instead of in one surge that would result in a great deal of energy loss and perhaps harm to the cell.

**Condensation and Hydrolysis Reactions**

The assembly of all four types of biological macromolecules involves the same type of chemical reaction—a condensation reaction between the monomers of each polymer. In a **condensation reaction**, an H atom is removed from a functional group on one molecule, and an OH group is removed from another molecule. The two molecules bond to form a larger molecule and water. Because the reaction results in the release of water, condensation reactions are also called **dehydration reactions**. An example of a condensation reaction is shown in **Figure 1.26**.

The breakdown of macromolecules into their monomers also occurs in cells. For example, during the digestion of a polysaccharide, your body breaks down the macromolecule into simpler sugars. This process involves the addition of water to break the bonds between the monomers. In a **hydrolysis reaction**, an H atom from water is added to one monomer, and an OH group is added to the monomer beside that one. The covalent bond between these monomers breaks and the larger molecule is split into two smaller molecules.

Condensation reactions and hydrolysis reactions can be thought of as opposite reactions, and a single chemical equation can be used to represent them. Chemical equations showing the condensation and hydrolysis reactions that are involved in the synthesis and breakdown of each of the four classes of biological molecules are shown in **Figure 1.27** on the opposite page.

---

**Figure 1.26** In a condensation reaction (A), two molecules are joined by a covalent bond, and water is produced as a side product. In a hydrolysis reaction (B), a larger molecule is broken apart through the addition of water at each break point.
Carbohydrates, lipids, proteins, and nucleic acids are assembled by condensation reactions among their monomers, and these polymers are broken down by hydrolysis reactions. The double arrow indicates that a chemical reaction can proceed in a "forward" and a "reverse" direction. As written, the forward is a condensation reaction and the reverse is a hydrolysis reaction. Note that the rings in the carbohydrate and nucleotide structures are drawn in this manner so that a particular molecule is not specified.

**Figure 1.27** Carbohydrates, lipids, proteins, and nucleic acids are assembled by condensation reactions among their monomers, and these polymers are broken down by hydrolysis reactions. The double arrow indicates that a chemical reaction can proceed in a "forward" and a "reverse" direction. As written, the forward is a condensation reaction and the reverse is a hydrolysis reaction. Note that the rings in the carbohydrate and nucleotide structures are drawn in this manner so that a particular molecule is not specified.
Enzymes Catalyze Biological Reactions

A certain amount of energy is required to begin any reaction. This energy is referred to as the **activation energy** of a reaction. If the activation energy for a reaction is large, it means the reaction will take place very slowly. If the chemical reactions of cells were carried out in a test tube, most would occur too slowly to be of any use to the cell. For example, suppose you performed the reaction of carbon dioxide with water to form carbonic acid, which is part of the buffering system to control blood pH. You would determine that it proceeds quite slowly. Perhaps 200 molecules of carbonic acid would form in about one hour. Reactions this slow are of little use to an organism. One way to increase the rate of any chemical reaction is to increase the temperature of the reactants. In living systems, however, this approach to speeding up reactions has a major drawback. The temperatures at which chemical reactions would need to occur to proceed quickly enough to sustain life are so high that they would permanently denature proteins. This is why a long-lasting fever can be dangerous. If the fever stays too high for too long, major disruptions to cellular reactions occur, and in some cases they can be fatal.

Another way to increase the rate of chemical reactions without increasing temperature is to use a catalyst. A **catalyst** is a substance that speeds up a chemical reaction but is not used up in the reaction; it can be recovered unchanged when the reaction is complete. As shown in Figure 1.28, catalysts function by lowering the activation energy of a reaction. Cells manufacture specific proteins that act as catalysts. A protein molecule that acts as a catalyst to increase the rate of a reaction is called an **enzyme**. In red blood cells, for example, an enzyme called carbonic anhydrase enables carbon dioxide and water to react to form about 600 000 molecules of carbonic acid each second!

Almost all chemical reactions in organisms are facilitated by enzymes. The types of chemical reactions discussed in this section are all catalyzed by enzymes. In fact, each example of the different types of reaction is carried out with its own characteristic enzyme. Thus, enzymes not only increase the rate of a chemical reaction, but also do so in a highly specific manner through specific interactions between the enzyme and the reactant(s) for the reaction.

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**Learning Check**

25. Identify the products of a neutralization reaction, and explain how the reaction changes the properties of the reacting acid and base.

26. What happens to the electrons that are lost by a compound that is undergoing an oxidation reaction?

27. Explain why a redox reaction must involve changes to two molecules simultaneously.

28. Does a molecule have more energy in its oxidized or reduced form? Explain.

29. Differentiate between a hydrolysis reaction and a condensation reaction.

30. There are four major types of chemical reactions that break apart and build biological molecules. For each type, write a sentence that summarizes a key defining feature that distinguishes it from the others.

---

**Figure 1.28** Catalysts, such as enzymes, reduce the activation energy required for a reaction to begin.

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**Enzymes** are biological macromolecules that catalyze, or speed up, chemical reactions in biological systems.
Enzymes Bind with a Substrate

Like other proteins, enzymes are composed of long chains of amino acids folded into particular three-dimensional shapes, with primary, secondary, tertiary, and often quaternary structures. Most enzymes have globular shapes, with pockets or indentations on their surfaces. These indentations are called active sites. The unique shape and function of an active site are determined by the sequence of amino acids in that section of the protein.

As shown in Figure 1.29, an active site of an enzyme interacts in a specific manner with the reactant for a reaction, called the substrate. During an enzyme-catalyzed reaction, the substrate joins with the enzyme to form an enzyme-substrate complex. The substrate fits closely into the active site, because enzymes can adjust their shapes slightly to accommodate substrates. Intermolecular bonds, such as hydrogen bonds, form between the enzyme and the substrate as the enzyme adjusts its shape. The change in shape of the active site to accommodate the substrate is called induced fit.

Enzymes prepare substrates for reaction by changing the substrate, its environment, or both in some way, and thus lowering the activation energy of the reaction. Depending on the enzyme, this process may occur in a variety of ways. For example, the active site may:

- contain amino acid R groups that end up close to certain chemical bonds in the substrate, causing these bonds to stretch or bend, which makes the bonds weaker and easier to break;
- bring two substrates together in the correct position for a reaction to occur;
- transfer electrons to or from the substrate (that is, reduce or oxidize it), destabilizing it and making it more likely to react;
- add or remove hydrogen ions to or from the substrate (that is, act as an acid or base), destabilizing it and making it more likely to react.

Once the reaction has taken place, the products of the reaction are released from the enzyme. The enzyme is now able to accept another substrate and begin the process again. This cycle is known as the catalytic cycle. Some enzymes require the presence of additional molecules or ions to catalyze a reaction. Organic molecules that assist an enzyme are called coenzymes. Some enzymes require the presence of metal ions, such as iron or zinc, which are referred to as cofactors. Your body requires small amounts of minerals and vitamins in order to stay healthy. In many cases, this is because those minerals and vitamins are essential to enzyme activity. Without them, enzymes in your body cells cannot catalyze reactions.
**Enzyme Classification**

Enzymes are classified according to the type of reaction they catalyze. For example, enzymes that catalyze hydrolysis reactions are classified as hydrolases. Because the shape of an enzyme must match its substrate exactly, most enzymes are specific, catalyzing just one specific reaction. Not surprisingly, therefore, thousands of different enzymes exist to catalyze the numerous reactions that take place in organisms. Each enzyme is provided with a unique name, in order to properly identify it. The names of many enzymes consist of the first part of the substrate name, followed by the suffix “-ase.” For example, the hydrolase enzyme that is responsible for catalyzing the cleavage of the glycosidic linkage in the disaccharide lactose is named lactase.

---

**Activity 1.3  Enzymes in the Food and Pharmaceutical Industries**

Enzymes are used various ways in the food and pharmaceutical industries. For example, they may be used:

- as medicines (for example, to aid in digestion and to treat digestive disorders such as pancreatitis);
- to manufacture certain medicines (for example, certain antibiotics, anti-inflammatory products, and clot-dissolving preparations);
- to manufacture and/or process foods and food products (for example, breads, food products that contain eggs, and food products that contain fruits and vegetables).

In this activity, you will do research to find out about the roles and uses of enzymes in the preparation of various foods, food products, and medicines.

**Procedure**

1. Choose an application of enzymes either in the food and food processing industry or in the pharmaceutical industry. Examples of applications you might choose include the following:
   - enzymes to weaken or strengthen wheat gluten
   - enzymes to derive sweeteners from starch
   - enzymes to produce cheese flavourings
   - enzymes to assist in food allergies and intolerances
   - enzymes to increase yields and improve health benefits of fruit and vegetable juices
   - enzymes to reduce bitterness in protein-containing foods
   - enzymes to improve colour in teas and coffees
   - enzymes to produce penicillin
   - enzymes to treat muscle and joint inflammation
   - enzymes to treat pancreatitis
   - enzyme formulations for use in conjunction with other medicines to reduce required dosage and/or side effects

2. Use print resources, electronic resources, or both to learn which enzyme or enzymes may be used and how they are used. Where possible, investigate the techniques that were used before the adoption of enzymes for the same purpose.

3. Record your findings in the form of a table or some other suitable format of your choice.

**Questions**

1. Summarize, using a format and reporting style of your choice, the ways in which enzymes are used in the application you researched and the importance of enzymes to that application.
Enzyme Activity Is Influenced by Surrounding Conditions

Enzyme activity is affected by any change in condition that alters the enzyme's three-dimensional shape. Temperature and pH are two important factors that can cause this alteration. When the temperature becomes too low, the bonds that determine enzyme shape are not flexible enough to enable substrate molecules to fit properly. At higher temperatures, the bonds are too weak to maintain the enzyme's shape. As shown in Figure 1.30, enzymes function best at an optimal temperature range and range of pH values. These ranges are fairly narrow for most enzymes. Most human enzymes work best within the range of pH 6 to 8. Some enzymes, however, function best in very acidic environments, such as is found in the stomach. For example, because pepsin acts in the acidic environment of the stomach, its optimum pH is much lower than that of trypsin, which acts in the small intestine.

Although enzymes bind and catalyze substrates very quickly, the formation of an enzyme-substrate complex will take longer if there are few substrates present. For example, in a dilute solution of substrate, enzymes and substrates will encounter each other less frequently than they will in a concentrated solution of substrate. For this reason, enzyme activity generally increases as substrate concentration increases. This is true up to a certain point, when the enzymes in the solution are working at maximum capacity. Past this point, adding more substrate will not affect the rate of the reaction.

![Figure 1.30](image-url)

**Figure 1.30** The activity of an enzyme is affected by (A) temperature and (B) pH. Most enzymes in humans, such as trypsin, which helps break down protein in the small intestine, work best at a temperature of about 40°C and a pH of between 6 and 8. Pepsin is an enzyme that acts in the stomach, an acidic environment, so its optimum pH is about 2.

**Predict** the activity of trypsin in the stomach.
Enzyme Activity Is Regulated by Other Molecules

Inhibitors are molecules that interact with an enzyme and reduce the activity of the enzyme. They do this by reducing an enzyme's ability to interact with its substrate. As shown in Figure 1.31, this interference in substrate binding can occur by two different mechanisms: competitive inhibition and non-competitive inhibition. Competitive inhibitors interact with the active site of the enzyme. When both the substrate and an inhibitor are present, the two compete to occupy the active site. When the inhibitor is present in high enough concentration, it will out-compete the substrate for the active site. This blocks the substrate from binding, and the reaction that the enzyme normally catalyzes does not occur.

In addition to an active site, many enzymes have an allosteric site. Other molecules that bind to this site can alter the activity of the enzyme by altering the conformation or three-dimensional shape of the enzyme. Non-competitive inhibitors bind to an allosteric site on an enzyme. This causes the conformation of the enzyme to change in such a way as to reduce its ability to interact with the substrate at its active site. As a result, there is a decrease in the activity of the enzyme. As you will learn in Unit 2, many biochemical reactions are grouped together in pathways. The product of one reaction acts as a substrate for the enzyme that catalyzes the next reaction in the pathway. A common way that biochemical pathways are regulated is by a process called feedback inhibition. In feedback inhibition, the product of the last reaction of the pathway is a non-competitive inhibitor of the enzyme that catalyzes a reaction at the beginning of the pathway. This form of regulation is a way that the cell has for ensuring that products of a pathway are not produced unnecessarily. When enough product is available, its synthesis and all the reactions related to its synthesis are turned off or reduced.

**inhibitor** a molecule that binds to the allosteric or active site of an enzyme and causes a decrease in the activity of that enzyme

**allosteric site** a site on an enzyme that is not the active site, where other molecules can interact with and regulate the activity of the enzyme

**activator** a molecule that binds to the allosteric site of an enzyme and keeps an enzyme active or causes an increase in the activity of that enzyme

Suggested Investigation
Plan Your Own Investigation
1-B Investigating Factors Affecting Enzyme Activity

**Figure 1.31** In competitive inhibition, a substance binds to the active site of an enzyme, preventing substrates from binding. In non-competitive inhibition, such as allosteric inhibition, an inhibitor prevents the enzyme from working, but the inhibitor does not bind to the active site.

**Activator** molecules can also bind to an allosteric site. In this case, the conformation of the enzyme alters in such a way as to cause an increase in enzyme activity. The regulation of enzyme activity by activators and inhibitors binding to allosteric sites is called allosteric regulation.
Fabry Disease: A Serious Result of Enzyme Deficiency

Fabry disease, a rare condition that affects one in every 40 000 men and one in every 100 000 women, occurs today in about 250 Canadians. It is caused by a deficiency in a lysosomal enzyme called α-galactosidase A. Alpha-galactosidase A is one of many types of enzymes in the lysosomes of cells. These enzymes act on proteins, fats, nucleic acids, and sugars to either break down or transform them. Without the action of lysosomal enzymes, these substances can build up in cells, leading to toxic effects.

Normally, α-galactosidase A will break down its substrate, globotriaosylceramide (Gb3), through a hydrolysis reaction. Gb3 is a glycolipid—a type of lipid molecule with a carbohydrate tail attached. In Fabry disease, a defect in the gene that codes for α-galactosidase A prevents the gene product from folding properly. This prevents the enzyme from carrying out its usual function—breaking down Gb3. The resulting build-up of Gb3 in cells causes widespread damage to tissues and organs. Symptoms of Fabry disease include skin spots, fatigue, and pain, as well as heart problems, kidney damage, and strokes.

ENZYME REPLACEMENT THERAPY The idea of replacing the α-galactosidase A activity that patients with Fabry disease are lacking gave rise to Enzyme Replacement Therapy (ERT) for the disease. This therapy is the result of recombinant DNA technology, in which copies of the human enzyme are produced by inserting DNA into cells cultured in vitro. The recombinant α-galactosidase A enzyme is then injected into patients to help replenish the enzyme levels. Although the replacement therapy is not a cure, the treatment can give patients some relief from symptoms.

LACK OF FUNDING FOR ORPHAN DISEASES Controversy has accompanied ERT since its approval in 2004. ERT is extremely expensive (about $300 000 per year per person). Because Fabry disease is so rare, scientists are having a hard time enrolling enough people in studies to draw strong conclusions about how well the treatment works. Some patients were given a supply of ERT in manufacturer-run clinical trials and on compassionate grounds, but on a temporary basis only. When access was halted in 2005, patients staged a two-day rally calling for government funding for ongoing treatment. The federal government teamed up with manufacturers and the provincial/territorial governments in 2007 to co-sponsor a $100 million, three-year clinical trial that delivered treatment to patients. But when funding ended, patients’ access to treatment was again at risk. Although Ontario has since led negotiations to continue funding for treatment through the drug trial, rare-disease advocacy groups are seeking a more permanent, long-term solution for this and other orphan diseases. Like orphans who lack parental support, these diseases do not receive sufficient support in terms of research, funding, and awareness, due to the low incidence of these diseases in the population. Advocacy groups argue that a national orphan disease medication program should be established.

Connect to Society

1. What policies govern the coverage of orphan disease treatments in other countries such as the United States, Australia, and Japan? What is the status of the development of a national policy in Canada? Who are stakeholders in advocating for and implementing such a policy in Canada, and what is the Ontario government’s role? List the advantages and disadvantages of implementing a national orphan drug policy from the point of view of each stakeholder.

2. Enzyme replacement therapy is one of many examples of new technological applications for enzymes in medicine. Research the use of enzymes as treatments for other medical conditions. How and why are enzymes used to treat these conditions?
Section 1.3 Review

Section Summary

- A neutralization reaction is a reaction between an acid and a base, producing water and a salt as products. Buffers in biological systems ensure that changes in pH are minimized.
- In a redox reaction, electrons are transferred between substances.
- In a condensation reaction, two or more molecules are linked together and a water molecule is released per bond formed. In a hydrolysis reaction, a large molecule such as a polymer is broken down into smaller molecules, as water is added to bonds between monomers.
- An enzyme is a protein that catalyzes a chemical reaction, enabling it to proceed faster than it otherwise would do. The basic mechanism of action involves a substrate that fits into the active site of the enzyme to form an enzyme-substrate complex.
- Many enzymes have an allosteric site, where inhibitors or activators may bind to regulate enzyme activity. Enzyme activity is also affected by factors such as temperature, pH, and concentration of substrate.

Review Questions

1. **K/U** Identify each type of reaction.
   a. \(2\text{NaOH} + \text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O}\)
   b. \(\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}\)
   c. glycine + glycine \rightarrow dipeptide
   d. sucrose \rightarrow glucose + fructose
2. **K/U** Record one more different example of each type of reaction that you identified in question 1.
3. **C** Prepare a sketch that shows how a non-competitive inhibitor affects enzyme activity. Include a short written description of how this type of inhibition works.
4. **K/U** Give one example of how each type of reaction is used in a biological system.
   a. condensation reaction
   b. hydrolysis reaction
   c. neutralization reaction
   d. redox reaction
5. **K/U** What is the importance of buffers in biological systems? Provide one detailed example.
6. **A** Predict the effects of consuming too many antacids on healthy gastric enzyme activity in the human digestive system.
7. **C** Prepare a sketch showing how a competitive inhibitor affects enzyme activity. Include a short written description of how this type of inhibition works.
8. **C** Use a Venn diagram to compare and contrast competitive and non-competitive inhibition.
9. **K/U** Describe how an enzyme acts to change the rate of a chemical reaction in a biological system. Include the term activation energy in your answer.
10. **T/I** A biochemist is given an unknown biological compound. The biochemist tests the compound and obtains the following results:
    - One molecule of the compound contains between 15 and 20 atoms.
    - The compound dissolves in water.
    - When the compound is dissolved in water, the solution has a pH of 5.
    - When the solution is heated, a reaction takes place that produces larger molecules. Based on these results, give one specific suggestion for what this biological compound might be. Explain your answer.
11. **K/U** An enzyme is isolated from a cell culture but is found to have lost its function. What factors would you examine as you try to restore the ability of the enzyme to catalyze reactions?
12. **T/I** A biologist heated an enzyme-catalyzed reaction slowly over 20 min at 1°C per minute, starting at 20°C. From 0 to 9 minutes, the rate of reaction increased from 3 mol/s to 7 mol/s. From 9 to 11 min, the rate of reaction dropped quickly to 0.4 mol/s. From 11 to 20 min, the rate of reaction gradually increased from 0.4 mol/s to 0.9 mol/s.
    a. Use the data provided in the description to construct a rough graph of rate of reaction versus temperature for the enzyme-catalyzed reaction.
    b. Analyze your graph, explaining each change in the rate. For example, why did the rate increase from 0 to 9 min? What happened at 9 min? What might have happened between 11 and 20 min?
Identifying Biological Macromolecules in Food

Biochemists have developed standard tests to determine the presence of the most abundant macromolecules made by cells: carbohydrates (sugars, starches), lipids (fats), and proteins. In this investigation, your group will conduct some of these standard tests to identify the presence of sugar, starch, lipid, and protein in known samples. You will then use the same tests to analyze different food samples for the presence of these macromolecules. The class test results of various foods will then be combined and analyzed.

Pre-Lab Questions

1. Why are you required to wear safety eyewear and protective clothing while conducting this investigation?
2. Why must the test tubes be thoroughly cleaned and dried when one part of the procedure is completed, before starting the next part of the procedure?
3. What colours indicate a positive test and a negative test for proteins, sugar, and starch for the indicators used in this investigation?

Question

What biochemical macromolecules are present in different food samples?

Procedure

In the first four parts of the procedure, you will learn how to perform different tests to identify protein, starch, sugar, and fat. Some of these tests involve the use of an indicator—a chemical that changes colour when it reacts with a specific substance. When performing these tests:

- add the indicator by holding the dropper bottle over the test tube and allow the drops to “free-fall” into the solution. Do not touch the inside wall of the test tube with the dropper bottle.
- give each tube a gentle shake after adding the indicator, in order to make sure that the solution is properly mixed. You can do this by gently tapping the side of the tube with your finger.

Part 1: Test for Proteins

Biuret reagent has a blue colour that changes to violet in the presence of proteins.

1. Use a millimetre ruler and a wax pencil to mark and label four clean test tubes at the 2 cm and 4 cm levels. Fill each test tube as follows:
   - Test tube 1: Fill to the 2 cm mark with distilled water, and then add Biuret reagent to the 4 cm mark.
   - Test tube 2: Fill to the 2 cm mark with albumin solution, and then add Biuret reagent to the 4 cm mark. (Albumin is a protein.)
   - Test tube 3: Fill to the 2 cm mark with pepsin solution, and then add Biuret reagent to the 4 cm mark. (Pepsin is an enzyme.)
   - Test tube 4: Fill to the 2 cm mark with starch suspension, and then add Biuret reagent to the 4 cm mark.
2. Be sure to tap or swirl each tube to mix the solutions. Record your results and conclusions in a table like the one that follows.

<table>
<thead>
<tr>
<th>Biuret Test for Protein</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Tube</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

3. Dispose of the contents of the test tubes as directed by your teacher. Clean and dry the test tubes.

### Part 2: Test for Starch

Iodine solution turns from a brownish colour to a blue-black in the presence of starch.

1. Use a millimetre ruler and a wax pencil to mark and label two clean test tubes at the 1 cm level. Fill each test tube as follows:
   - Test tube 1: Fill to the 1 cm mark with starch suspension, and then add five drops of iodine solution. (Be sure to shake the starch suspension well before taking your sample.)
   - Test tube 2: Fill to the 1 cm mark with distilled water, and then add five drops of iodine solution.

2. Note the final colour change. Record your results and conclusions in a table like the one that follows.

<table>
<thead>
<tr>
<th>Iodine Test for Starch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Tube</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

3. Dispose of the contents of the test tubes as directed by your teacher. Clean and dry the test tubes.

### Part 3: Test for Sugars

Sugars react with Benedict's solution after being heated in a boiling water bath. Increasing concentrations of sugar give a continuum of colours, as shown in the following table.

<table>
<thead>
<tr>
<th>Typical Reactions for Benedict's Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical</strong></td>
</tr>
<tr>
<td>distilled water</td>
</tr>
<tr>
<td>glucose</td>
</tr>
<tr>
<td>maltose</td>
</tr>
<tr>
<td>starch</td>
</tr>
</tbody>
</table>

1. Use a millimetre ruler and a wax pencil to mark and label five clean test tubes at the 1 cm and 3 cm levels. Fill each test tube as follows:
   - Test tube 1: Fill to the 1 cm mark with distilled water, and then add Benedict's solution to the 3 cm mark.
   - Test tube 2: Fill to the 1 cm mark with glucose solution, and then add Benedict's solution to the 3 cm mark.
   - Test tube 3: Put a few drops of onion juice in the test tube. Fill to the 1 cm mark with distilled water, and then add Benedict's solution to the 3 cm mark.
   - Test tube 4: Put a few drops of potato juice in the test tube. Fill to the 1 cm mark with distilled water, and then add Benedict's solution to the 3 cm mark.
   - Test tube 5: Fill to the 1 cm mark with starch suspension; add Benedict's solution to the 3 cm mark.

2. Heat all five test tubes in a boiling water bath for about 5 min.

3. Note the final colour change. Record your results and conclusions in a table like the one that follows.

<table>
<thead>
<tr>
<th>Benedict's Test for Sugars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Tube</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>

4. Dispose of the contents of the test tubes as directed by your teacher. Clean and dry the test tubes.
Part 4: Test for Fats

Fats leave a translucent, oily spot on paper. Liquid fats penetrate paper, while solid fats rest predominantly on top.

1. Place a small drop of distilled water on a square of brown paper. Describe the immediate effect.
2. Place a small drop of vegetable oil on a square of brown paper. Describe the immediate effect.
3. Place a small quantity of butter or margarine on a square of brown paper. Describe the immediate effect.
4. Wait about 5 min. Examine each piece of paper to determine which test material penetrates the paper. Record your results and conclusions in a table like the one that follows.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>distilled water</td>
<td></td>
</tr>
<tr>
<td>oil (liquid fat)</td>
<td></td>
</tr>
<tr>
<td>butter or margarine (solid fat)</td>
<td></td>
</tr>
</tbody>
</table>

**Part 5: Testing for the Presence of Biochemical Macromolecules in Foods**

1. Your teacher will give you four small samples of the first foodstuff to be tested.
2. Prepare solid samples for testing by mashing them with a mortar and pestle, and adding a few drops of distilled water.
3. Using the procedures followed in parts 1 to 4, test the sample for the presence of each of protein, starch, sugar, and fat.
4. Record your results and conclusions in a table. Suggested headings for the table are provided below.

<table>
<thead>
<tr>
<th>Food Sample</th>
<th>Test</th>
<th>Results</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>protein</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>starch</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>sugar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fat</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Dispose of the contents of the test tubes as directed by your teacher. Clean and dry the test tubes.
6. Repeat steps 1 to 5 for each of the food samples.

**Analyze and Interpret**

1. Why was distilled water tested?
2. Describe any limitations to the usefulness of these tests for food samples.

**Conclude and Communicate**

3. Describe a positive test for:
   a. protein
   b. starch
   c. sugars
   d. fats (lipids)
4. The class tested a number of food samples. Did any of the results surprise you? Explain your answer.

<table>
<thead>
<tr>
<th>Extend Further</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. <strong>Inquiry</strong> Starch is digested into sugars by the enzyme amylase. Design a procedure that could be used to measure amylase activity.</td>
</tr>
<tr>
<td>6. <strong>Research</strong> In this investigation, you performed qualitative tests for the presence of certain biochemical substances. How are the relative quantities of these biochemical substances determined? Use the Internet or other sources to learn more about quantitative testing methods.</td>
</tr>
</tbody>
</table>
Plan Your Own INVESTIGATION

Investigating Factors Affecting Enzyme Activity

The compound hydrogen peroxide, H₂O₂, is a by-product of metabolic reactions in most living organisms. However, hydrogen peroxide is damaging to molecules inside cells. As a result, nearly all organisms produce the enzyme peroxidase, which breaks down hydrogen peroxide as it is formed. Potatoes are one source of peroxidase. Peroxidase facilitates the breakdown of hydrogen peroxide into water and gaseous oxygen. This reaction can be detected by observing the oxygen bubbles generated.

In this investigation, you will design a procedure and, with your teacher’s approval, carry out experiments to test the effects of temperature and pH on peroxidase activity.

Pre-Lab Questions

1. What is an enzyme?
2. What is the substrate of the enzyme peroxidase? How do you know?
3. What is the effect of adding sodium hydroxide to an aqueous solution? What is the effect of adding hydrochloric acid?

Question

How effectively does the enzyme peroxidase work at different temperatures and pH values?

Hypothesis

Make a hypothesis about how you think temperature and pH will affect the rate at which the enzyme peroxidase breaks down hydrogen peroxide. Consider both low and high temperatures and pH values.

Plan and Conduct

1. Examine the materials provided by your teacher. As a group, list ways you might test your hypothesis.
2. Agree on a method(s) your group will use to test your hypothesis.
3. Your experimental design should include a control and test one variable at a time. Will you be collecting quantitative or qualitative data?
4. What will be your independent variable? What will be your dependent variable? How will you set up your control?
5. How will you determine peroxidase activity? How will you measure the amount of oxygen produced? Have you designed a table for collecting data?
6. Will you conduct more than one trial? How long will you allow each trial to run?
7. How will you analyze your data?
8. Write a numbered procedure for your investigation that lists each step, and prepare a list of materials that includes the amounts you will require. Before beginning the investigation, have your teacher check and approve your plan.

Safety Precautions

- Wear gloves and safety eyewear throughout this investigation.
- Hydrochloric acid and sodium hydroxide are corrosive. Avoid any contact with skin, eyes, or clothes.
- Flush spills on skin immediately with copious amounts of cool water and inform your teacher.
- Exercise care when heating liquids and using a hot plate.
- Take care when using sharp instruments.
- Do not taste any substances in the laboratory.

Suggested Materials

- 0.1 mol/L hydrochloric acid, HCl
- 0.1 mol/L sodium hydroxide, NaOH
- 3% hydrogen peroxide, H₂O₂
- raw peeled potato
- ice
- test tubes, rack, and marker
- beaker for hot water bath
- hot plate
- beaker tongs
- medicine droppers
- distilled water
- scalpel or sharp knife
- ruler
- forceps
- clock or timer
- thermometer or probe
- pH indicator paper or probe
Analyze and Interpret

9. Draw graphs showing the relationship between temperature and oxygen produced, and between pH and oxygen produced.

Conclude and Communicate

10. What did this investigation indicate about the activity of peroxidase?

11. At what temperature did peroxidase work best? at what pH?

12. What was the purpose of using control samples?

13. Do your data support or disprove your hypothesis? Explain.

14. Infer how the presence of hydrochloric acid affects the activity of peroxidase.

15. If you have ever used hydrogen peroxide as an antiseptic to treat a cut or scrape, you know that it foams as soon as it touches an open wound. Account for this observation.

16. INQUIRY Design an investigation in which you use hydrogen peroxide to test for the presence of peroxidase in other foods, such as pieces of other vegetables or meat. Determine which food shows the greatest peroxidase activity. Explain the differences in enzyme activity among different foods. With permission from your teacher and with suitable safety precautions in place, carry out your investigation.

17. RESEARCH The human body contains peroxisomes, which are microscopic organelles in cells that contain enzymes to detoxify substances, such as hydrogen peroxide. Research disorders that affect peroxisomes and the symptoms these disorders cause. What are some advances in cellular biology that are being used to treat these disorders?
### Section 1.1 Chemistry in Living Systems

The properties and interactions of biologically important molecules determine their function in living systems.

**Key Terms**
- isotope
- radioisotope
- molecule
- organic molecule
- biochemistry
- intramolecular
- intermolecular
- hydrogen bond
- hydrophobic
- hydrophilic
- ion
- functional group

**Key Concepts**
- Organisms are composed primarily of the chemical elements carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur.
- Intramolecular interactions occur between atoms within a molecule, forming chemical bonds.
- The polarity of a molecule influences the intermolecular interactions that occur between molecules. Two important types of intermolecular interactions are hydrogen bonding and hydrophobic interactions.
- The functional group or groups on a molecule determine the properties of the molecule. Important functional groups in biological molecules include hydroxyl, carboxyl, carbonyl, amino, sulfhydryl, and phosphate groups.
- The structures of molecules can be represented using a variety of formats. Structural formulas are two-dimensional representations that indicate how the atoms are bonded together. Space-filling models are a common way to represent the three-dimensional structures of molecules.

### Section 1.2 Biologically Important Molecules

Carbohydrates, lipids, proteins, and nucleic acids (for example, DNA and RNA) are important macromolecules that are a part of living systems.

**Key Terms**
- macromolecule
- polymer
- monomer
- carbohydrate
- monosaccharide
- isomer
- disaccharide
- polysaccharide
- lipid
- triglyceride
- fatty acid
- phospholipid
- lipid bilayer
- steroid
- wax
- protein
- amino acid
- polypeptide
- nucleic acid
- DNA (deoxyribonucleic acid)
- RNA (ribonucleic acid)
- nucleotide

**Key Concepts**
- Carbohydrates can act as short-term energy-storage and structural biological molecules. They include polysaccharides, and disaccharides and monosaccharides (sugars). Polysaccharides are macromolecules composed of monosaccharide monomers.
- Lipids are longer-term energy storage and structural biological molecules that contain a higher proportion of non-polar C–C and C–H bonds than carbohydrates. Triglycerides, phospholipids, steroids, and waxes are different types of lipids.
- Proteins are macromolecules composed of amino acid monomers. Proteins have primary, secondary, tertiary, and sometimes quaternary structures, which are essential for their function. Proteins enable chemical reactions in living systems, and also perform a wide variety of structural and regulatory roles.
- Nucleic acids are macromolecules composed of nucleotide monomers. DNA and RNA are both nucleic acids. DNA stores the hereditary information of a cell. RNA plays a central role in the synthesis of proteins.
Section 1.3 | Biochemical Reactions

Chemical reactions that take place in living systems include neutralization, oxidation, reduction, condensation, and hydrolysis reactions, many of which may be catalyzed by enzymes.

Key Terms
- acid
- base
- pH scale
- neutralization reaction
- buffer
- oxidation
- reduction
- redox reaction
- condensation reaction
- hydrolysis reaction
- activation energy
- catalyst
- enzyme
- active site
- substrate
- enzyme-substrate complex
- inhibitor
- allosteric site
- activator

Key Concepts
- A neutralization reaction is a reaction between an acid and a base, producing water and a salt as products. Buffers in biological systems ensure that changes in pH are minimized.
- In a redox reaction, electrons are transferred between substances.
- In a condensation reaction, two or more molecules are linked together and a water molecule is released per bond formed. In a hydrolysis reaction, a large molecule such as a polymer is broken down into smaller molecules, as water is added to bonds between monomers.
- An enzyme is a protein that catalyzes a chemical reaction, enabling it to proceed faster than it otherwise would do. The basic mechanism of action involves a substrate that fits into the active site of the enzyme to form an enzyme-substrate complex.
- Many enzymes have an allosteric site, where inhibitors or activators may bind to regulate enzyme activity. Enzyme activity is also affected by factors such as temperature, pH, and concentration of substrate.

Knowledge and Understanding

Select the letter of the best answer below.

1. How is a polymer formed from multiple monomers?
   a. from the growth of the chain of carbon atoms
   b. by the removal of an –OH group and a hydrogen atom
   c. by the addition of an –OH group and a hydrogen atom
   d. through hydrogen bonding
   e. through intermolecular forces

2. Which carbohydrate would you find as part of a molecule of RNA?
   a. galactose
   b. deoxyribose
   c. ribose
   d. glucose
   e. amylase

3. A triglyceride is a form of _____ composed of _____.
   a. lipid; fatty acids and glucose
   b. lipid; fatty acids and glycerol
   c. lipid; cholesterol
   d. carbohydrate; fatty acids
   e. lipid; fatty acids and glycerase

4. What makes starch different from cellulose?
   a. Starch is produced by plant cells, and cellulose is produced by animal cells.
   b. Cellulose forms long filaments, while starch is highly branched.
   c. Starch is insoluble, and cellulose is soluble.
   d. All of the above.
   e. None of the above.

5. Which of the following does not belong?
   a. methane
   b. cyclohexane
   c. propanol
   d. sodium chloride
   e. water

6. Cholesterol is a precursor for which of the following?
   a. testosterone
   b. fatty acids
   c. trans fat
   d. phospholipids
   e. All of the above are synthesized from cholesterol.

7. Which of the following is not primarily composed of protein?
   a. hair
   b. urine
   c. nails
   d. enzymes
   e. collagen
8. Identify which of the following reactions would result in the production of water.
   a. hydrolysis reaction
   b. formation of a disulfide bond
   c. formation of a peptide bond
   d. breaking a disaccharide
   e. All of the above will produce water.

9. A polypeptide chain is held together by
   a. hydrolysis bonds
   b. glucose linkages
   c. peptide bonds
   d. disulfide bridges
   e. phosphate linkages

10. Which of the following factors do not impact enzyme activity?
    a. changes in temperature
    b. changes in substrate concentration
    c. changes in pH
    d. changes in ionic concentrations
    e. All of the above impact enzyme activity.

11. Allosteric sites are responsible for
    a. regulating enzyme activity
    b. denaturing an enzyme
    c. increasing the substrate concentration
    d. decreasing the substrate concentration
    e. forming hydrogen bonds

12. Which statement regarding enzymes is false?
    a. Enzymes speed up reaction rate.
    b. Enzymes lower the activation energy of a reaction.
    c. Enzyme reaction rate increases with temperature up to a certain point.
    d. Enzyme reaction rate decreases as the concentration of substrate increases.
    e. All of the above are true regarding enzymes.

13. A reaction produces water as a product. Which statement regarding the reaction is false?
    a. A condensation reaction may have occurred.
    b. A dehydration reaction may have occurred.
    c. A neutralization reaction may have occurred.
    d. A hydrolysis reaction may have occurred.
    e. All of the above are true.

14. Which part of an amino acid has the greatest influence on the overall structure of a protein?
    a. the –NH₂ amino group
    b. the R group
    c. the –COOH carboxyl group
    d. Both a and c
    e. None of the above.

Answer the questions below.

15. What are two main carbon-containing molecules in organisms?
16. Identify the property of water that allows for hydrogen bonding.
17. Summarize the steps in protein folding.
18. How would the function of an enzyme be affected if human body temperature increased?
19. Identify the differences between a condensation reaction and a hydrolysis reaction.
20. What is the role of an allosteric inhibitor?
21. How does a buffer assist in cellular function?
22. Would enzyme denaturation occur at the primary, secondary, or tertiary structure? Explain.
23. What is the role of an allosteric site in enzyme activity?
24. Differentiate between coenzymes and cofactors.
25. List two changes that could cause an enzyme to denature.
26. What is the difference between an organic molecule and an inorganic molecule? Provide two examples of each.
27. What happens to enzyme activity when slight deviations in pH or temperature are introduced?
28. Identify the monomer for each type of polymer as well as the general type of reaction required to make the polymer.
    a. protein
    b. glycogen
    c. RNA
29. Differentiate between an isotope and a radioactive isotope.
30. In three sentences or fewer, describe how the four main types of biological macromolecules differ and what they have in common.

Thinking and Investigation

31. Hypothesize what would happen to an enzyme if a substrate covalently bonded with the active site.
32. Infer what happens to the function of amylase when it is digested.
33. Genetic mutations that result in an improvement in enzyme function are rare. Draw a conclusion as to why most changes are devastating to an enzyme.
34. Enteric coatings are applied to medication to prevent stomach acid from breaking down the medication prior to delivery. Cellulose, which is indigestible by humans, was initially investigated as a coating material before being modified.
   a. Although enzymes do not exist in humans to digest cellulose, a pharmacologist discovers that some medication is entering circulation. Propose a mechanism that explains this.
   b. Currently, cellulose is modified with succinate, a naturally occurring compound produced in the metabolism of sugar. Infer why this method is a highly reliable method of releasing medication in the small intestine.

35. Use your understanding of the properties of intermolecular and intramolecular forces to explain the fact that water rises in narrow tubes, against the force of gravity, as shown in the diagram below.

36. In the mid-1990s, bread machines became very popular as they provided optimal conditions (such as a specific temperature) for yeast to produce carbon dioxide, causing the dough to rise.
   a. Explain why a specific temperature is optimal for this process.
   b. Outline steps you would take to determine the optimal temperature for yeast activity using an apparatus found in the kitchen.
   c. What variables would you hold constant to ensure accurate testing?
   d. How could you measure carbon dioxide production accurately?

37. A vegetarian has become lactose intolerant but wishes to continue consuming dairy products as a source of protein and nutrients. He plans to take a minimum amount of a lactase digestive supplement to avoid excess exposure to pharmaceuticals, yet still enjoy dairy products. To determine the minimum amount, he breaks each tablet into four pieces each. On the first morning, he takes eight pieces—equivalent to the recommended dosage. Each day he consumes one fewer piece until his lactose intolerance is felt. After evaluating his procedure, make three suggestions that would ensure the most accurate result possible.

38. Artificial enzymes are roughly 1000 times less efficient than naturally occurring enzymes. Make two inferences that could explain this difference.

39. The production of corn syrup from starch involves the hydrolysis of the starch into simple sugars.
   a. What are the drawbacks to using acid to catalyze this reaction?
   b. Suggest an alternative that would be faster and safer.

40. Manpreet conducts an investigation to determine the rate of enzyme activity. She places a known amount of starch in a carefully measured amylase solution and times the reaction. After one hour she measures the concentration of glucose. Explain the flaw in her procedure that limits the usefulness of her conclusions.

41. Detection of HIV occurs through a process called enzyme-linked immunosorbent assay, or ELISA. In this test, enzymes are linked to proteins in the immune system called antibodies. When the protein-based antibody comes in contact with the protein markers on the virus, the enzyme causes a visible colour change. Why must scientists pay special attention to pH, ionic concentrations, and temperatures during these assays?

42. A starch solution is placed into dialysis tubing and suspended in distilled water. The distilled water contains amylase, the salivary enzyme that breaks down starch, as well as Benedict’s solution for detecting glucose. The mixture is heated for 10 minutes, but the colour remains red. Evaluate each of the following statements for accuracy.
   a. The enzyme is inactive since the starch was not broken down.
   b. The dialysis tubing must not be permeable to the enzyme.
   c. Benedict’s solution will not detect glucose when it is bound to the enzyme.
43. A biologist is investigating an hypothesis linking decreased brain function to fatty acid levels in the body. How can a baseline measurement of fat be obtained from cellular tissue? Use your knowledge of laboratory practices and common sense to suggest a strategy.

44. Salivary amylase can be collected by having an individual salivate into a test tube for several minutes. A group of three students each perform an investigation in which their own amylase sample is used to break down starch. Results are accurately measured. When complete, one student's sample still contains a large amount of starch and very little glucose.
   a. All three students conclude that this result must be caused by a slower enzyme via a less specific active site. Is this the only explanation? Explain.
   b. How could the accuracy of the investigation be improved?

45. A biologist heats a beaker containing a clear, colourless aqueous solution of an unknown biological substance. After a few hours, the solution begins to thicken. The biologist knows that either a hydrolysis or condensation reaction took place. Based on the observations available, which type of reaction might have occurred, and why?

46. Hydrogen bonds and hydrophobic interactions play important roles in stabilizing and organizing biological macromolecules.
   a. Describe how hydrogen bonds and hydrophobic interactions affect the form and function of proteins.
   b. Infer how a disruption in the hydrogen bonds of nucleic acids would affect form and function.
   c. Infer how a disruption in hydrophobic interactions would affect form and function in lipids.

47. To produce buttons, a piece of plastic is fastened to a steel backing using a high-pressure hand press. To create an analogy for enzyme activity, identify what represents the enzyme and what represents the substrates in this process. How is the “enzyme” here different from a biological enzyme?

48. Use your understanding of enzymes and protein folding to infer how having a fever helps fight bacterial infection.

49. Communication
   a. Name the chemical reaction that is taking place.
   b. Write a caption for this diagram that explains what is happening.
   c. Use the same style as is used in this diagram to draw the chemical reaction that is effectively the opposite of the one shown.

50. Before the structure of DNA was discovered, the proportion of adenine and thymine in DNA was always found to be identical. The same was not true for adenine and uracil in RNA. Based on this, infer the structural differences between DNA and RNA and draw a diagram to show the differences.

51. Lipids, carbohydrates, and proteins all contain different amounts of energy per unit mass. Propose a procedure that would qualitatively show the energy differences among these macromolecules.

52. Construct a graph illustrating the concentrations of reactants and products in an enzyme-catalyzed reaction. How does your graph compare to a non-catalyzed reaction?

53. Draw a graph to show the trend of the data you would expect when comparing enzyme activity and substrate concentration.

54. List the various foods you have eaten today. Use an asterisk to indicate which food has the best representation of all the macromolecules discussed in this chapter.

55. In a table or other graphic organizer, differentiate between RNA and DNA.

56. Make a labelled sketch to show the features of hydroxyl, –OH, that make it a polar functional group.

57. Explain in an email to a classmate why it would be difficult to find an enzyme that functions at a very low pH.

58. Construct a Venn diagram to compare and contrast condensation and hydrolysis reactions.
59. A healthy diet contains more complex carbohydrates than simple sugars. Based on what you have learned about monosaccharides and polysaccharides, draw a simple diagram to illustrate the difference between simple sugars and complex carbohydrates.

60. Explain clearly, with the assistance of a diagram, whether oxidation can occur without the presence of oxygen.

61. Sketch a representation of the condensation and hydrolysis of the molecules listed below. Design symbols to represent the molecules involved. The symbols will be used for a class of grade 7 students, who do not have any understanding of the chemistry concepts related to structural and molecular formulas. Explain your reasoning for designing each symbol as you did.
   a. a disaccharide from two molecules of glucose
   b. a triglyceride from one molecule of glycerol and three fatty acid molecules
   c. a dipeptide from two amino acid molecules

62. Clearly explain how an enzyme can take part in a reaction that involves sucrose but not in a reaction that involves maltose.

63. Summarize your learning in this chapter using a graphic organizer. To help you, the Chapter 1 Summary lists the Key Terms and Key Concepts. Refer to Using Graphic Organizers in Appendix A to help you decide which graphic organizer to use.

Application

64. Technological applications that affect biological processes and cellular functions are used in the food, pharmaceutical, and medical industries. Fluorine is often added to medication to prevent the body from breaking the medication down quickly. Since F is highly electronegative, what factor may be responsible for the slow degradation?

65. Would you expect the following amino acid to be soluble in water? After copying the figure into your notebook, clearly label the regions of the molecule that support your solubility decision. These areas should be referenced in your explanation.

66. Biological molecules and their chemical properties affect cellular processes and biochemical reactions. Arctic fish produce large amounts of antifreeze proteins during cold winter months. These proteins prevent water from forming large ice crystals and damaging soft tissue. Would you expect these proteins to be hydrophobic or hydrophilic? Explain your answer with reference to the role of the proteins.

67. Heat shock proteins are produced when cells are subjected to elevated temperatures. These proteins minimize the need for new enzyme synthesis when temperature conditions return to normal. What do you think is the function of heat shock proteins with respect to other proteins in the cell?

68. Why is an understanding of hydrogen bonding essential to the study of biochemistry?

69. Mucus in the nasal passage is produced by cells that line the airways. Mucus is composed of glycoprotein (protein with carbohydrate side chains) and water. It ensures that airways are kept moist and that drainage occurs regularly. When mucus fails to drain, it often becomes the site of an infection requiring antibiotics.
   a. Where do the bacteria come from that lead to the infection?
   b. Why is a non-draining sinus an ideal location for a bacterial infection?
   c. Under normal circumstances, how would the bacteria be handled by the body?

70. The production of high-fructose corn syrup relies on enzymes for the conversion of starch to simple sugars. What features of the active site would be characteristic of this enzyme?

71. Use your knowledge of polarity to explain why methane, CH₄, has a low boiling point and is a gas at room temperature.

72. Enzymes intended for use in laboratory work are always shipped in a buffer solution. Explain why.

73. Use what you know about the polarities and charge distributions of water and biological molecules to explain how you think the interactions of biological molecules would be different if the liquid of biological systems was a non-polar molecule oil instead of water.

74. In artificial DNA replication, a crucial step involves the heating of DNA to near boiling temperatures prior to enzyme-based replication. What happens to the DNA when it is heated?
Select the letter of the best answer below.

1. (K/U) Which of these provides the most accurate information about the shape of a molecule?
   a. electron model  
   b. structural formula  
   c. molecular formula  
   d. space-filling model  
   e. compound formula

2. (K/U) What feature could help distinguish between two carbohydrates?
   a. ratio of C:H:O  
   b. boiling point  
   c. mass  
   d. internal energy  
   e. None of the above

Use the diagram below to answer questions 3 - 5.

3. (K/U) The molecule shown is best described as:
   a. polar  
   b. charged  
   c. ionic  
   d. hydrophilic  
   e. non-polar

4. (K/U) In which part of the molecule is the stored energy that is most important in chemical reactions?
   a. in the nucleus of each atom  
   b. in the covalent bonds  
   c. in the ionic bond  
   d. in the electrons  
   e. in the polar regions

5. (K/U) Which term best describes the structure of the molecule?
   a. linear  
   b. cross-shaped  
   c. pyramidal  
   d. trapezoidal  
   e. tetrahedral

6. (K/U) Condensation reactions are known for:
   i. producing acid  
   ii. producing water  
   iii. occurring in acid  
   iv. consuming water  
   v. attaching two amino acids
   a. i and iii  
   b. iii and iv  
   c. iii, iv, v

7. (K/U) The shape and charge distribution of a protein are important because
   a. the shape changes over time as the protein ages, giving it new properties  
   b. these properties govern the function of each protein  
   c. the charge and shape are identical for most proteins  
   d. proteins define life  
   e. proteins have no chemical bonds

8. (K/U) A carbon atom can make a maximum of ___ covalent bonds.
   a. one  
   b. two  
   c. three  
   d. four  
   e. six

9. (K/U) The chemical elements that are most common in living systems are
   a. C, S, Fe, H, N  
   b. C, Cl, Mg, Fe, H  
   c. C, H O, N, P  
   d. C, I, Na, K, O  
   e. C, H, O, F, P

10. (K/U) An example of a condensation reaction would be
    a. building amino acids from proteins  
    b. building lipids from fatty acids  
    c. breaking down glucose into starch  
    d. breaking down starch into glucose  
    e. none of the above

Use sentences and diagrams as appropriate to answer the questions below.

11. (K/U) Why does water expand when it freezes?

12. (C) A classmate asks, “What happens when an allosteric inhibitor enters the active site of the enzyme?” What would you tell your classmate?

13. (C) Use a diagram to illustrate a peptide bond. Write a caption to go with your illustration, describing the formation of a peptide bond in words.

14. (K/U) Write a word equation for a general neutralization reaction.
15. **K/U** Explain what a functional group is, and state two characteristics that make functional groups important to living systems.

16. **A** Redox reactions occur in non-living systems as well as in living systems.
   a. State a general definition for a redox reaction.
   b. Demonstrate how the reaction between a sodium atom and a chlorine atom to form the ionic compound sodium chloride is a redox reaction.

17. **A** Infer why cattle chew the same grass for an extended period of time.

18. **T/I** Identify the following reactions as oxidation, reduction, redox, neutralization, condensation, or hydrolysis. Give reasons for your identification in each case. (You are not required to name any of the compounds in these reactions.)
   a. CH₃O–H + HO–CH₃ → CH₃–O–CH₃ + H₂O
   b. CH₃NH₂ + HO–H → CH₃NH₃⁺ + HO⁻
   c. CH₄ + O₂ → CH₂O + H₂O
   d. H₂ → 2H⁺ + 2e⁻
   e. O₂ + 4H⁺ + 4e⁻ → 2H₂O
   f. 2H₂ + O₂ → 2H₂O
   g. C₆H₁₂O₆ + 6O₂ → 6CO₂ + 6H₂O
   h. CH₃O–CH₃ + H₂O → CH₃O–H + HO–CH₃
   i. CH₃COO–H + CH₃NH₂ → CH₃COO⁻ + CH₃NH₃⁺
   j. Cl₂ + 2e⁻ → 2Cl⁻

19. **C** Examine the structural diagram below.

   ![Structural Diagram]

   a. Identify the type of molecule this is.
   b. Copy the structural diagram, and add labels to identify all five features that characterize this type of molecule.
   c. Identify the one feature that is significant for determining the distinctive shape and properties of polymers of this type of molecule.
   d. Explain, with the aid of a diagram, how two different molecules of this type may join together to form a polymer.

20. **K/U** Explain what activation energy is, and explain the role of enzymes in relation to activation energy and chemical reactions.

21. **A** The diagrams below show an enzyme called lysozyme that hydrolyzes its substrate, which is a polysaccharide that makes up the cell walls of bacteria. Write a detailed caption that could be used to accompany these two diagrams in a textbook.

22. **C** Design a summary chart to record the type, structure, examples, and functions of the four types of macromolecules.

23. **A** What are the advantages of having a particular biochemical reaction such as the breakdown of a sugar proceed as a set of pathways, rather than as just a single reaction?

24. **T/I** It used to be common for textbooks to use an analogy of a lock and key to describe the mechanism by which substrates bind to the active site of an enzyme.
   a. Infer how this lock-and-key analogy works, and write a brief description of it.
   b. Name the model that is considered more accurate than the lock-and-key model for enzyme-substrate interaction, and explain why it is more accurate.

25. **C** Explain to a grade 6 school student the property of water that makes it an excellent transporter of nutrients.