Chemistry for Biology 1190 Students

Chemistry for Biology 1190 Students

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Final Assessment Instructions

Biology 1190 Chemistry

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Introduction

Welcome to Biology 1190 Chemistry!

The purpose of this module is to equip you with the basic chemistry knowledge you will require to understand human body cell structure and function. Chemistry is the scientific study of the organization and interactions between matter and within matter. Because the human body is made of matter, understanding the structure and properties of matter will help you understand the body.

You can decide how to use this module for your studies. Some recommended ways include:

- Working through the module from start to finish.
- Starting with the final assessment as a "placement test", then reviewing only those sections of the module with which you had trouble.
- Completing only the sections you feel you have forgotten.
- Completing only the sections you feel you have never understood or have trouble understanding from your previous studies.

Regardless of how you choose to use this module, **you are responsible for this information.** You may see any of the terms contained within this module on any quiz or exam. If you have any questions or require clarification on the material within this module, please see your instructor.

If you have issues using the module, contact juliawong@langara.ca

CHAPTER 1: ATOMS

Matter is anything that has **mass** and takes up space. All matter in the universe, including the human body, is made of **atoms**.

Atoms are composed of three **subatomic particles:** electrons, protons, and neutrons. **Electrons** are negatively charged and have negligible mass. **Protons** are positively-charged and **neutrons** have no charge but both protons and neutrons have measurable mass. The protons and neutrons reside in a dense central location called the atomic **nucleus** and the electrons surround the nucleus.

There are many models to describe atomic structure, including the Bohr model of the atom and the electron cloud model. The **Bohr model** proposes that electrons act like particles and surround the nucleus in discrete energy layers or **electron shells** (Figure 1). Every electron shell can accommodate a specific number of electrons or a specific amount of **energy**. This is because electrons move rapidly and, therefore, possess **kinetic energy** or the energy of movement. For example, the first shell is the energy shell closest to the nucleus. This shell can accommodate two electrons. The second and third shells can each accommodate a maximum of eight electrons. Some atoms have more than three electron shells but the atoms examined in this course will generally possess a maximum of three electron shells. *The farther an electron is from the nucleus, the more energy that electron has.* In other words, the outermost electron shell of an atom is the highest energy shell. Electrons fill the lowest energy or most stable shells first: the electron shells closest to the nucleus.

The electron cloud model proposes that electrons act like waves and their position can be described as a cloud around the nucleus. This course will not use the electron cloud model extensively but understanding the basic concept underlying this model will help you understand noncovalent interactions and more complex medical topics, such as medical imaging in your future studies.

Electrons determine the important properties and behaviour of atoms, especially when interacting with other atoms.

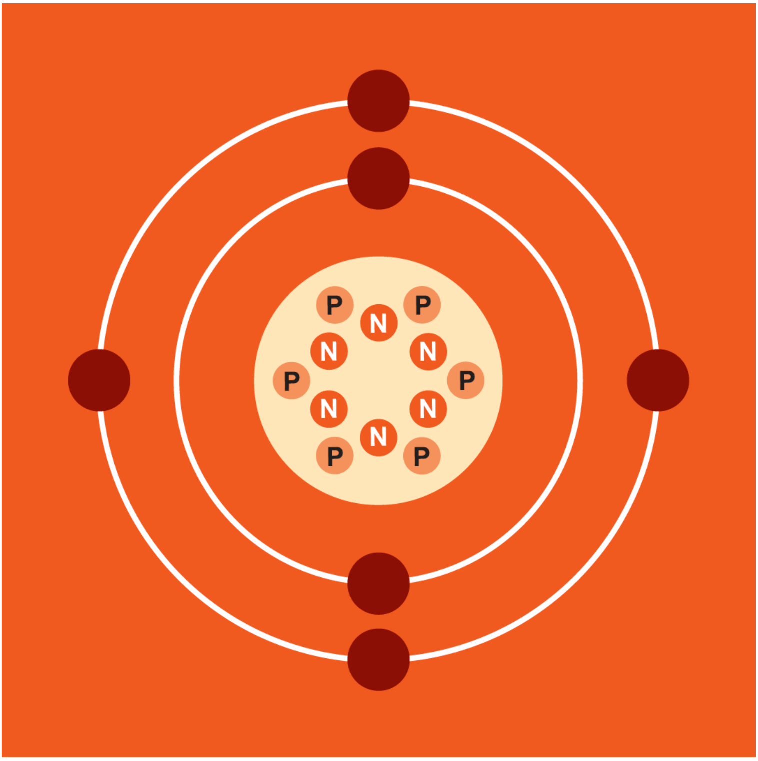


Figure 1. Bohr model of a carbon atom. The atomic nucleus contains six (6) *protons. Therefore, the atomic number of carbon is six* (6). *This carbon atom is uncharged. Therefore, the number of electrons is also six* (6).

Elements are matter composed of only one type of atom and elements differ by the number of subatomic particles. Elements are identified by a unique **atomic number.** The atomic number corresponds to the *number of protons* in the nucleus. In an uncharged element, the number of protons (positive charges) is equal to the number of electrons (negative charges). The **mass number** of an element is the total number of protons and neutrons in the nucleus. The **periodic table of elements** organizes elements by increasing atomic number (left to right) and other atomic properties. **For this course, you do not need to memorize the periodic table of elements.**

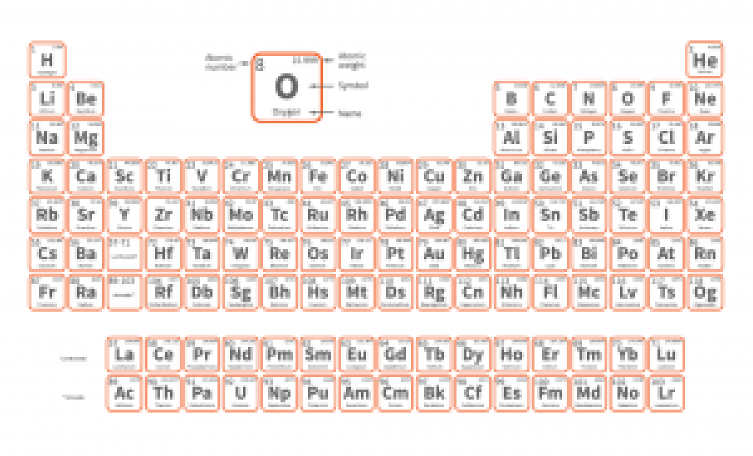
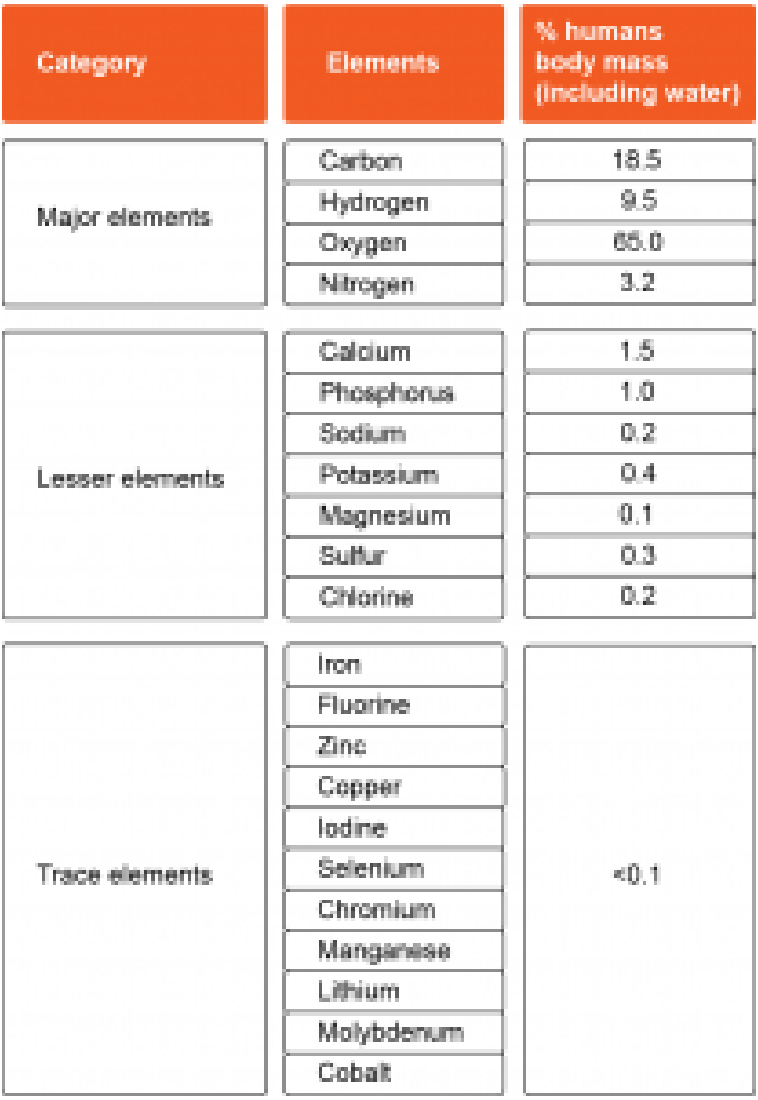


Figure 2. The periodic table of elements.

Every organism has a unique set of **essential elements** or elements required for life. Humans require **25 essential elements**; plants require 17 essential elements. Some essential elements are required in large amounts because they are common in our cells, such as carbon, hydrogen, oxygen, and nitrogen (Table 1). These are the **major elements.** Some essential elements are required in smaller quantities: the **lesser elements**. Some essential elements are required in minute quantities: the **trace elements**.

Table 1: Major, lesser, and trace elements of the human body.



Category	Elements	% humans body mass (including water)
Major elements	Carbon	18.5
	Hydrogen	9.5
	Oxygen	65.0
	Nitrogen	3.2
Lesser elements	Calcium	1.5
	Phosphorus	1.0
	Sodium	0.2
	Potassium	0.4
	Magnesium	0.1
	Sulfur	0.3
	Chlorine	0.2
Trace elements	Iron	<0.1
	Fluorine	
	Zinc	
	Copper	
	Iodine	
	Selenium	
	Chromium	
	Manganese	
	Lithium	
	Molybdenum	
	Cobalt	

Source: Wikipedia. (https://en.wikipedia.org/wiki/Composition_of_the_human_body)

Though trace elements are required in tiny amounts, there are serious consequences to **deficiencies.** For example, the recommended daily intake (RDI) of iodine is 150 micrograms (µg) for 19–30 year old adults who are not pregnant or breast-feeding. You can easily meet the RDI by using a small amount of iodized table salt on food or by consuming dairy or seafood.[1]. However, an iodine deficiency may result in an enlargement of the thyroid gland or **goiter**. The thyroid makes important hormones called T3 and T4 that contain many molecules of iodine in their structure. Without sufficient iodine, the thyroid enlarges to make more thyroid hormones to compensate for the low levels of T3 and T4.

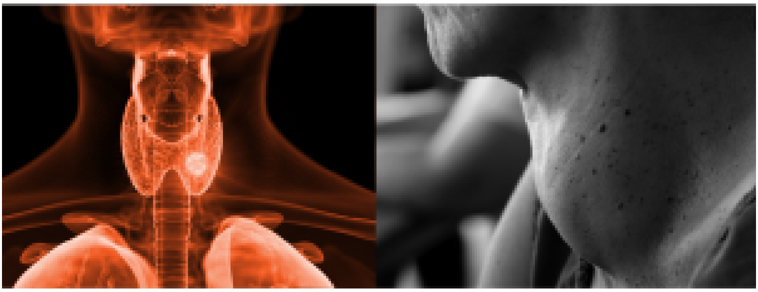


Figure 3A. The thyroid gland is located at the base of the neck (above left). Enlargement of the thyroid gland is called a goiter (above right). *Hyperthyroidism at the throat by Freelanceman is licenced by AdobeStock under* CC BY 2.0

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1. source: Government of Canada: https://www.canada.ca/en/health-canada/services/food-nutrition/healthy-eating/dietary-reference-intakes/tables/reference-values-elements-dietary-reference-intakes-tables-2005.html

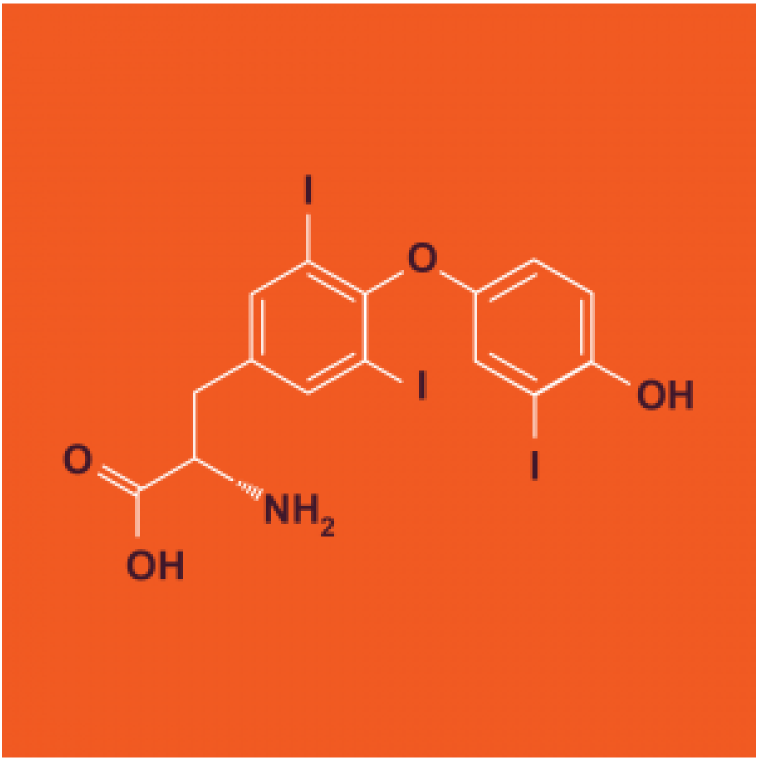

Figure 3B. The structure of thyroid hormone T3 contains iodine.

Elements with the same atomic number but different mass numbers are called **isotopes**. These elements differ by the number of *neutrons* in the nucleus and some isotopes are commonly used for medical imaging or treatments. For example, iodine has an atomic number of 53 and a mass number of 127. An isotope of iodine, iodine-131, possesses **four** additional neutrons and is used to treat **thyroid cancer.**

Iodine-131 is also **radioactive**, meaning the atom is unstable and can emit **radiation. Ionizing radiation** is the emission of particles or waves that disrupt the structure of matter upon collision, resulting in damage to important cellular molecules such as DNA. For example, iodine-131 emits high energy electrons (beta emission) and a gamma ray. Gamma rays are high energy waves that can break double-stranded DNA and stop the cell from replicating or copying its DNA. This kills the cell.

Chemistry in the clinic:

Cancer is a complex disease but, for the purposes of Biology 1190, we can start by defining cancer as uncontrolled cell division. An individual with **thyroid cancer** suffers from uncontrolled cell division within the thyroid gland. To treat thyroid cancer, the patient is **infused** with iodine-131 in their blood. The blood carries the radioactive iodine-131 to the thyroid gland and the beta and gamma emissions of the radioactive isotope kill the cancerous thyroid cells. Some normal healthy cells may be killed or damaged by iodine-131 treatment. However, the damage may be repaired after treatment or that damage may be tolerated to kill the rapidly growing cancer. Iodine-131 is just one example of a medically useful radioactive isotope. Other radioactive isotopes are used to diagnose and to treat diseases and disorders.

Summary:

- All matter is made of atoms.
- Atoms are made of a nucleus containing protons and neutrons. Electrons surround the nucleus.
- Elements are matter made of one type of atom and have unique properties due to their unique atomic structures.
  - Essential elements are elements that are necessary to support life.
    - Major elements are required in large amounts; lesser elements are required in smaller amounts.
    - Trace elements are required in very small amounts.

- Elements play important roles in human health and medicine.

Chapter 1 Quiz - Part 1

Complete the following questions to practice and apply your knowledge from this chapter. Written responses will **not** be scored but you can mark your own responses using the solutions provided. Multiple choice and fill-in-the-blank questions will be scored to help you assess your progress. Good luck!

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Chapter 1 Quiz - Part 2

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CHAPTER 2: CHEMICAL BONDS AND MOLECULES

A **molecule** is matter that contains more than one atom. Molecules that contain more than one element in a fixed ratio are called **compounds**. Atoms in molecules and compounds are held together by **chemical bonds**. Chemical bonds are forces between atoms that hold them together.

The outermost electron shell of an atom is called the **valence shell** and the electrons within that shell are called **valence electrons**. Recall: the valence electrons are the highest energy electrons. The valence electrons may be transferred or shared with other atoms. The **valence number** of an element is the number of electrons required to fill the valence shell.

Activity: Drag and drop the correct valence number under the corresponding atom.

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Reactive elements are elements with *incomplete valence shells*. For example, hydrogen (H) has an atomic number of 1. The valence shell is the first shell and that shell contains only 1 electron. The first shell can accommodate two electrons, so the valence shell is *incomplete* and H is reactive. Generally, these atoms will share or transfer valence electrons easily. In contrast, **inert elements** are elements with *full or complete valence shells*. These atoms do not share or transfer electrons easily. For example, helium (He) has an

atomic number of two. The valence shell of He is the first shell and it contains the maximum two electrons. Therefore, He is inert.
Activity: Drag and drop the correct valence number, number of valence electrons, and atomic number in the indicated boxes. Drag and drop the appropriate reactive or inert label under the correct atom.

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Ionic bonds

Reactive atoms that are close to filling their valence shells will pull on the valence electrons of nearby atoms with force. This property is called **electronegativity**. The closer an atom is to filling its valence shell, the more electronegative that atom is. For example, chlorine (Cl) has an atomic number of 17. The valence shell of Cl contains seven out of a total possible eight electrons. Cl requires only one electron to fill its valence shell and it is very **electronegative** compared to sodium (Na), for example. Na has an atomic number of 11 and its valence shell contains one out of a possible eight electrons. Therefore, Cl will pull on the single valence electron of Na with force. Na will **transfer** its valence electron to Cl, resulting in two **ions**: Na^+ because Na has transferred a valence electron to Cl and Cl^- because it has gained an electron. The two oppositely charged ions are *attracted* to one another. The resulting electrostatic attraction between Na^+ and Cl^- is called an **ionic bond** and the resulting compound is sodium chloride (NaCl).

IMPORTANT: the transfer of an electron from Na to Cl is NOT the bond. The ionic bond is the **electrostatic attraction between the resulting ions**.

Activity: Select the correct electron from Na and drag it to the appropriate location to complete the electron transfer with Cl, forming two ions and an ionic bond.

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Covalent bonds

Atoms with similar electronegativities will not transfer electrons to form an ionic bond between one another. Instead, they may **share** electrons to form a **covalent bond**. For example, carbon (C) has an atomic number of 6 and hydrogen (H) has an atomic number of 1. The valence shell of H is the second shell and it is *half-full*. The valence shell of H is the first shell and it is also *half-full*. Therefore, these atoms have **similar electronegativities**. When they come into proximity of one another, the valence electrons of C will complete the valence of H atoms and vice versa. Because these atoms pull on the shared electrons with *equal force*, the bonds between C and H are **nonpolar covalent bonds**. The electrons are shared equally between the bonding partners.

In contrast, oxygen (O) has an atomic number of 8 and its valence shell is the second shell. O is much closer to filling its valence shell than H; therefore, **O is more electronegative than H**. O and H can react to form water (H_2O). In water, O and H will *share* their valence electrons to fill each other's valence shells. However, because O pulls on electrons with more force, the shared electrons tend to reside with O more often than with either H atom. That means that O carries a **partial negative charge (δ-)** and C carries a **partial positive charge (δ+)**, resulting in a **polar covalent bond** between the atoms. Covalent bonds are relatively strong bonds as compared to electrostatic interactions such as ionic or hydrogen bonds.

Activity: Drag and drop the correct type of covalent bonds that form methane (left) and water (right).

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IMPORTANT: Molecules and compounds are not the same thing!

The atoms in molecules are joined by **covalent bonds**. Compounds contain two different atoms joined by either covalent or ionic bonds. Molecular oxygen (O_2) is a molecule containing two of the same atoms joined by **nonpolar covalent bonds**. However, O_2 is not a compound because it contains only one type of atom. Water (H_2O) is both a molecule and a compound because the atoms in water are joined by covalent bonds and it contains two different atoms: O and H.

Activity: Read the statements below and decide whether the statements are true or false.

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Chemistry in the clinic:

The **polarity** of a molecule is determined by the polarity of the covalent bonds within the molecule as well as the way the bonds are arranged. For example, **carbon dioxide** (CO_2) is a **nonpolar molecule**, despite containing two atoms with very different electronegativities. In CO_2, carbon forms two double bonds to each of the two oxygen atoms. Because the electron pairs strongly repel one another, CO_2 takes on a linear shape (Figure 8). The two oxygens face away from one another symmetrically, effectively *cancelling the polarity of the C-O bonds*. For this reason, CO_2 is poorly soluble in aqueous solutions such as blood plasma. You will learn in a future lecture on blood that CO_2 must be converted into a soluble compound called carbonic acid (H_2CO_3) by the action of an enzyme called **carbonic anhydrase** in red blood cells.

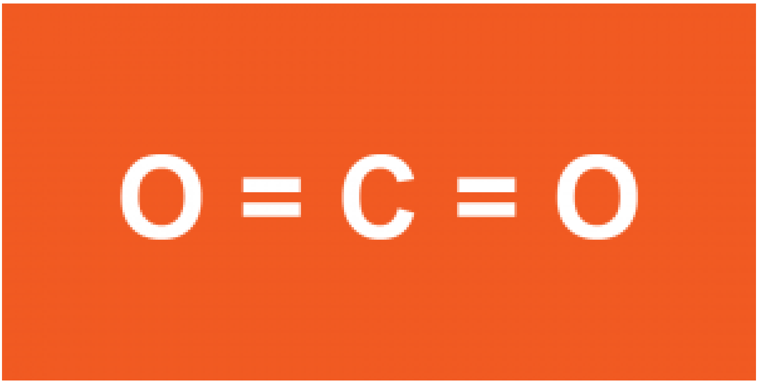

Figure 8. Carbon dioxide is a linear, nonpolar molecule

Interactions between molecules

The chemical bonds described above connect **atoms** *within* molecules or compounds. However, molecules can also interact with one another through chemical bonds and these interactions are collectively known as **intermolecular bonds**.

Hydrogen bonds

Recall: molecules such as water (H_2O) possess partial charges on their atoms. Electrostatic attraction between the partial negative charge **(δ-)** on the oxygen of one water molecule and the partial positive charges **(δ+)** on the hydrogens of *another* water molecule will be weakly attracted to one another. These interactions are relatively weak because the charges on the atoms are only *partial charges*. These weak **intermolecular interactions** that hold polar molecules together are called **hydrogen bonds**.

Activity: Identify the two types of bonds within and between water molecules and drag and drop the correct label next to the appropriate bond on the diagram below.

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We will explore the remarkable properties of water in the next chapter.

Hydrophobic interactions

Noncovalent interactions can occur between **nonpolar molecules** as well. Polar molecules interact favourably with other polar molecules. Therefore, polar molecules will arrange themselves to **exclude** nonpolar molecules in solution. These interactions will result in the association of nonpolar molecules with one another in aqueous solution, forming **hydrophobic interactions**. Though noncovalent, hydrophobic interactions are strong forces between molecules. In cells, hydrophobic interactions drive **protein folding**.

Nonpolar molecules are also held together by weak forces. Because electrons move quickly around the nucleus, there may be momentary differences in charge distribution within the electron clouds of atoms. This results in weak positive and weak negative areas of the electron cloud. The weakly positive portions of the electron cloud of one atom may be attracted to the weakly positive portions of another atom's electron cloud. These momentary electrostatic interactions between nonpolar molecules are called **van der Waal's forces**. Though individually weak, large nonpolar molecules may interact via hundreds of van der Waal's forces and, collectively, these forces form strong interactions between molecules. In cells, van der Waal's forces hold the nonpolar portions of lipids in cellular membranes together.

Chemical bonds hold atoms within a molecule together as well as molecules to other molecules. As a result, molecules within cells are arranged in a specific manner to reflect the **function** of those molecules within those organelles and cells.

Summary:

- Atoms are held together in molecules by chemical bonds
- The electronegativity of atoms affects the chemical properties

of the bonds those atoms form with other atoms to form molecules

- Bonds may be covalent or noncovalent
  - Covalent bonds involve the sharing of a pair of electrons
    - Polar covalent bonds form between atoms with different electronegativities
    - Nonpolar covalent bonds form between atoms with similar electronegativities
  - Noncovalent bonds include:
    - Ionic bonds where one atom transfers an electron to another more electronegative atom
    - Hydrogen bonds where one **polar molecule** is attracted to the opposite partial charges on **another polar molecule**
    - Strong hydrophobic interactions between nonpolar molecules
    - Weak van der Waal’s forces between nonpolar molecules

Chapter 2 Quiz - Part 1

Complete the following questions to practice and apply your knowledge from this chapter. Written responses will **not** be scored but you can mark your own responses using the solutions provided. Multiple choice and fill-in-the-blank questions will be scored to help you assess your progress. Good luck!

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Chapter 2 Quiz - Part 2

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CHAPTER 3: WATER

Water is essential for life. Life likely originated in water and water on Earth's surface continues to make Earth habitable. Water serves as a solvent for the chemical reactions inside and outside of cells that support life and water constitutes 60–90% of cell mass. In the human body, most metabolic reactions happen in water and water serves as a lubricant in body fluids. In this section, we explore how the chemical structure of water leads to its remarkable chemical properties that sustain life.

The structure of water

Recall: water (H_2O) is a compound consisting of only two elements: one oxygen atom and two hydrogen atoms. Oxygen is more electronegative than hydrogen; therefore, **polar covalent bonds** hold the atoms within water molecules together. The oxygen atom pulls with greater force on the shared electrons with hydrogen, resulting in a partial negative charge (δ-) on the oxygen atom. Each of the hydrogen atoms possess partial positive charges (δ+). In a solution of pure water, the partial negative charge on the oxygen is attracted to the partial positive charges on *other* water molecules, forming **hydrogen bonds between water molecules**. The hydrogen bonds between water molecules are responsible for all the properties of water.

The properties of water include:

1. Cohesion
2. High heat capacity
3. Expansion upon freezing
4. Versatility as a solvent

Water molecules exhibit cohesion

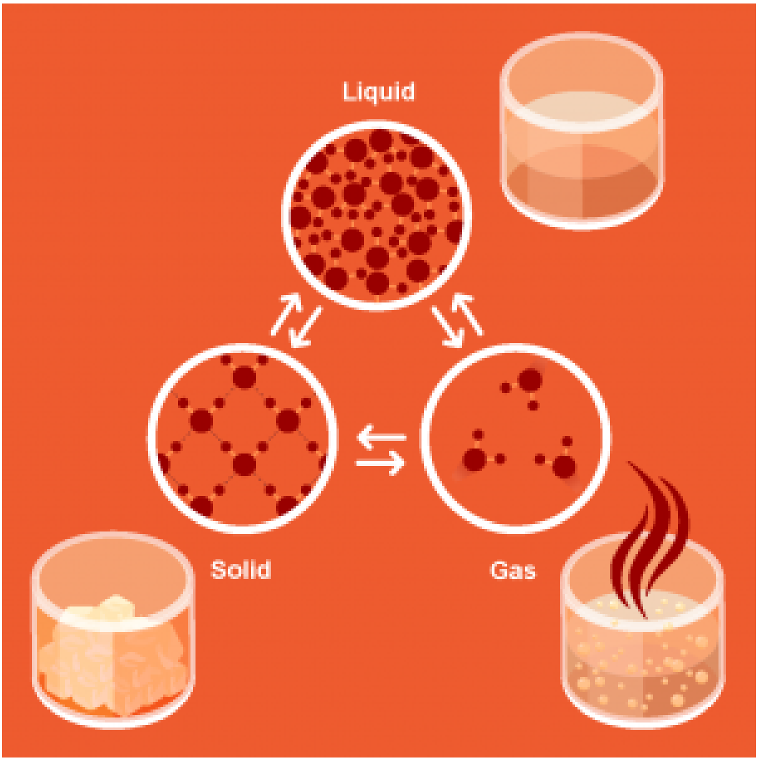
The hydrogen bonds between water molecules are weak relative to covalent bonds. However, water molecules tend to be attracted to other water molecules to form hydrogen bonds. The tendency for molecules to be attracted to one another if they are the same kind of molecules is called **cohesion**.

Cohesion allows water molecules to “stick together” via hydrogen bonding. Imagine a water droplet on the surface of your desk or table. Water droplets form because water molecules tend to be attracted to one another through hydrogen bonds rather than to your desk or table or to the air surrounding the water. This creates **surface tension** where water meets another type of matter. Water droplets form because of the cohesive properties of water!

In the human body, cohesion of water molecules ensures that when water moves in and out of thin-walled blood vessels called capillaries, one water molecule will be followed by many water molecules. This bulk movement of water ensures fluid balance within the body.

Water has a high heat capacity

Recall that the three states of matter include solid, liquid, and gas. When you think of water, you probably think of water in its **liquid state**. When water is *boiled*, the liquid is heated into a gas called **water vapour**. The water molecules move very fast in water vapour as compared to liquid water. When water is *frozen*, the liquid is cooled into **ice**. The water molecules in ice move much more slowly than in liquid water.



Recall that energy is the capacity to do work. Heat and temperature are two different measures of energy. **Heat** is the *total* **kinetic energy** within a system. **Temperature** is the *average* kinetic energy of a system. You may find it easier to understand the difference between these two measures of energy using the following example.

Water requires a large investment of heat energy before a small change in water temperature can occur. In other words, water has a **high heat capacity**. Imagine that you are boiling water to make tea. The amount of heat required to boil water is the *total amount of energy* you need to put in to raise the temperature of water to ~100°C. Water seemingly takes a long time to boil because energy must be invested to *break the hydrogen bonds that hold water molecules together* before those water molecules can move freely and form water vapour. Once the hydrogen bonds have been broken, individual water molecules move faster (gain kinetic energy), resulting in a *change in temperature*.

Similarly, boiled water takes a seemingly long time to cool. Once you have brewed your tea, you must wait for the tea to reach a drinkable temperature. As water cools, the molecules slow their movement and *energy is* ***released*** *as the hydrogen bonds between water molecules re-form*. That energy keeps the **temperature** of water relatively constant, even though you have stopped heating the water.

The high heat capacity of water makes Earth habitable. Heat from the atmosphere is absorbed by water in oceans, ensuring that the temperature on Earth's surface does not exceed a livable temperature. Water can release heat to cooler atmospheric air, again, keeping the temperature on Earth's surface relatively constant. Life on Earth is possible because of the ability of water molecules to form hydrogen bonds!

Water expands upon freezing

For most substances, the solid state of matter is **denser** than the liquid state of the same substance. As atoms and molecules slow their movement at low temperature, they get closer together. Generally, this increases the **density** of a substance.

Water is one exception to this rule. In liquid water, some molecules are bound together by hydrogen bonds but some molecules move freely. As liquid water freezes and hydrogen bonds form between water molecules, those hydrogen bonds form a geometrical pattern called a **lattice**. The fixed geometry of the lattice prevents water molecules from packing close together and, therefore, from becoming denser as it freezes. Instead, water **expands upon freezing**.

This is why ice floats in cold drinks and why liquid beverages cooled in the freezer may explode. Similarly, in the polar regions of the globe (high **latitudes**), ice forms over parts of the polar seas during cold seasons. The diverse marine life that lives in those oceans can survive cold seasons **because ice floats on top** and insulates the deeper water against colder atmospheric air.

Water is a versatile solvent

Water is the solvent for most of life's chemical reactions. A **solution** is a uniform mixture of liquid and substances dissolved in that liquid. A solution consists of a **solvent** or liquid and a **solute** or substance dissolved in the solvent.

Solution = solute(s) + solvent

Water is a polar molecule and a polar solvent. This means that water will dissolve other polar molecules as well as charged molecules. One example of a polar molecule is table sugar or sucrose ($C_{12}H_{22}O_{11}$). Sucrose stirred into water dissolves easily because both sucrose and water are polar molecules and the partial charges on the atoms of those molecules interact with one another favourably. The covalent bonds within sucrose are not easily weakened by water and remain intact when sucrose dissolves.

Charged molecules, such as table salt or **sodium chloride** (NaCI) also interact favourably with water. The partial negative charges on the oxygen atoms of water molecules attract the positively charged sodium ions; the partial positive charges on the hydrogen atoms of water molecules attract the negatively charged chloride ions. Because the partial charges of water can disrupt the electrostatic interactions between ions, ionic bonds are easily weakened by water. Therefore, water molecules tend to disrupt ionic bonds between ions and surround ions in solution, forming a **hydration sphere**.

Substances that interact favourably with water are called **hydrophilic**. Polar and charged solutes are hydrophilic and tend to dissolve easily in water.

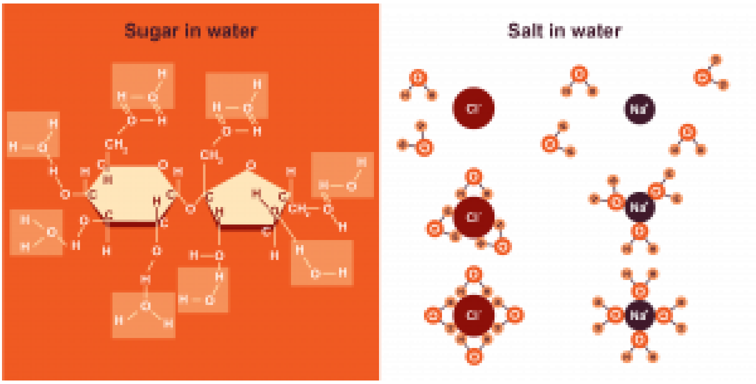


Figure 11. Dissolution of A. sucrose and B. salt in water

In contrast, nonpolar molecules bear no partial charges or full charges to interact favourably with partial charges on water molecules. Therefore, nonpolar molecules are called **hydrophobic**. Nonpolar solutes do not dissolve in water easily.

Chemistry in the clinic:

Colloids are suspensions of substances in a solvent-like liquid. Colloids differ from solutions by the **size of the particle in the liquid**. If the substance contains particles that measure between 1 nm and 1 µm (~ size of a bacterial cell), then the mixture is a **colloid** and not a solution. If the particles are smaller than 1 nm, then the mixture is a solution. **Blood plasma**, the liquid component of blood, is a colloid that contains relatively large proteins that are required for clotting. You will learn about the consequences of the colloidal nature of blood in a future lecture on the vascular system and hemodynamics.

$1 \text{ nm} = 1 \times 10^{-9} \text{ m}$

$1 \text{ µm} = 1 \times 10^{-6} \text{ m}$

Acids and bases

Pure water **dissociates** into two ions in solution: a proton (H^+) and a hydroxide ion (OH^-).

$$H_2O <=> H^+ + OH^-$$

Pure distilled water contains an equal amount of protons and hydroxide ions. However, if an **acid** is added to pure distilled water, then the resulting solution will contain more **protons** and the solution is **acidic**. **Acids** are substances that can donate a proton to solutions. Carbonic acid (H_2CO_3), for example, is formed in blood when CO_2 reacts with water in blood plasma. The resulting H_2CO_3 dissociates in aqueous solution into a proton and bicarbonate (HCO_3^-).

$$CO_2 + H_2O <=> H_2CO_3 <=> H^+ + HCO_3^-$$

Bases, on the other hand, accept protons from solution. Hydroxide and bicarbonate, for example, are bases because they are negatively charged ions that can accept protons from solutions. When bases are added to pure distilled water, the resulting solution will contain less protons relative to bases and will be **basic**.

The acidity of substances is measured on a logarithmic scaled called the **pH scale**. The pH scale ranges in value from 0 to 14. These values are the **negative logarithm of the concentration of protons [H^+] in solution**. Therefore, each step along the scale represents a 10-fold change in [H^+] in solution. The units of concentration are moles per litre (M).

$$pH = -\log_{10}[H^+]$$

Pure distilled water has a pH of 7 and this is considered **neutral** [neutral = neither acidic nor basic]. Acidic substances have a pH measuring *less than* 7. Carbonic acid has a pH of ~4.2, for example. Basic substances have a pH measuring *greater than* 7. Sodium bicarbonate, for example, has a pH of ~8.5.

Activity: Calculate the concentration of protons in each biological solution given in the diagram below. Drag and drop the correct concentration under the corresponding solution.

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Most of the solutions inside and outside of cells is kept within a very narrow pH range, generally around neutral pH. For example, blood must be kept between pH 7.35–7.45. Serious harm can result from blood pH falling outside of this range.

Substances that minimize changes in pH are called **buffers**. Buffers are molecules that can both donate protons to and accept protons from solutions to keep the pH of that solution constant. **Buffers DO NOT necessarily keep the pH of solutions neutral!** Some buffers keep solutions acidic; some keep solutions basic. Buffers simply prevent large changes in pH from occurring when acids or bases are added to solutions.

Chemistry in the clinic:

Abnormally *low* blood pH results in a condition known as **acidosis**. Acidosis results in the **denaturation** of cellular proteins, disrupting the ability of cells to control solute entry/exit and to make energy.

Similarly, abnormally *high* blood pH results in **alkalosis**. Alkalosis decreases the concentration of protons in body fluids as bases accept protons from solution. Alkalosis may also denature proteins and disrupt cellular function.

If left untreated, acidosis and alkalosis disrupt cell, tissue, and organ function, potentially leading to death. You may explore acidosis and alkalosis in more detail if you choose to take Biology 1191.

The primary regulator of blood pH is an enzyme called carbonic anhydrase in red blood cells. The action of carbonic anhydrase maintains blood buffering and is essential to human body function. This topic will be explored further in lectures about blood and the respiratory system.

Summary:

- Water is essential for cell function and life on Earth
- The atoms in a water molecule are held together by **polar covalent bonds**
- Molecules of water are held together by **hydrogen bonds**
- The hydrogen bonds of water are responsible for its remarkable properties, including:
    - Cohesion
    - Ability to moderate temperature
    - Expansion upon freezing
    - Versatility as a solvent
- Pure distilled water has a pH of 7 and is considered a neutral substance
- Acidic substances donate protons to solution and have a pH less than 7
- Basic substances accept protons from solution and have a pH greater than 7
- Buffers minimize changes to the pH of solution by donating or

accepting excess protons

Chapter 3 Quiz - Part 1

Complete the following questions to practice and apply your knowledge from this chapter. Written responses will **not** be scored but you can mark your own responses using the solutions provided. Multiple choice and fill-in-the-blank questions will be scored to help you assess your progress. Good luck!

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Chapter 3 Quiz - Part 2

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CHAPTER 4: CHEMICAL REACTIONS

Chemical reactions are the rearrangement of matter. For example, we have discussed the reaction between carbon dioxide and water to form carbonic acid. The atoms within the starting molecules are rearranged by *breaking the chemical bonds* between atoms and molecules, then *making new chemical bonds* between the resulting atoms and molecules. The input molecules into a chemical reaction are called **reactants** and the output molecules are called **products**. In cells, most chemical reactions are performed by proteins called **enzymes**.

Energy and energy transformations

Recall that energy is the capacity to do work. Some chemical reactions require an input of energy. The formation of carbonic acid (H_2CO_3) from CO_2 and H_2O requires an input of energy and is an **endergonic reaction**. However, the reverse reaction, where CO_2 and H_2O are formed from the breakdown of H_2CO_3 releases energy. Chemical reactions that release energy are called **exergonic reactions**.

Every chemical reaction will **transform energy**. **The first law of thermodynamics states that energy can neither be created nor destroyed.** The energy required or released from chemical reactions is not created nor lost by cells. The energy *already existed in the universe before the reaction occurred.* So, where does the energy come from for endergonic chemical reactions to proceed?

Outside of cells, the ambient heat energy provides the energy for chemical reactions to occur. The formation of carbonic acid under standard conditions (25°C, 1 atm) takes 60–90 seconds using ambient heat. That may seem like a short time, but cells require reactions to occur *much faster* to support life. Cellular reactions make use of **catalysts**: chemicals that increase the rate of chemical reactions without being changed by the reaction. Proteins called **enzymes** are cellular catalysts: they increase the rate of chemical reactions in cells.

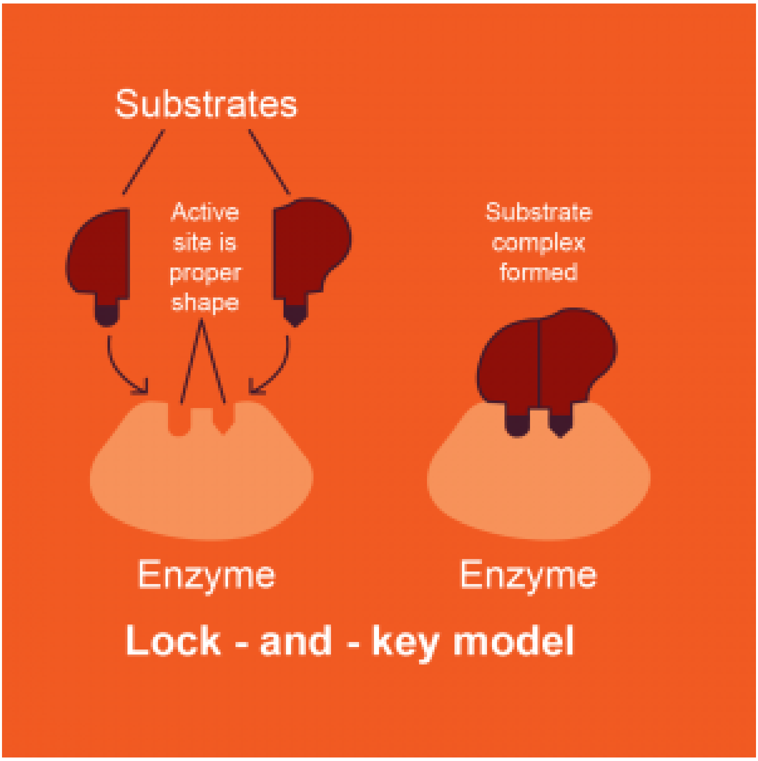

Figure 12. A. Enzyme-substrate interactions resemble a lock and key. B. Enzymes decrease the activation energy of chemical reactions to increase reaction rate.

How do enzymes speed up the rate of chemical reactions in cells? The reactants in an enzyme-catalyzed reaction have a special name: **substrates**. The conversion of substrates to products requires an energy investment. This energy is called **activation energy.** Activation energy is the energy required to weaken and rearrange the bonds of the substrates to form the products. Enzymes bind substrates at a specific location on the protein called the **active site** and the active site precisely fits the shape of the substrate(s), like a lock fits a key. The ability of enzymes to only bind its substrates is called **specificity**. At the active site, the enzyme positions the substrate(s) optimally for the conversion into product(s), thereby decreasing the time needed for the chemical reaction to occur.

Enzyme-catalyzed reactions follow the first law of thermodynamics, like all matter in the universe. The energy for chemical reactions performed by enzymes must come from somewhere. In cells, many chemical reactions are powered by the consumption of chemical sources of energy such as ATP. The energy invested is used to rearrange the chemical bonds within the substrates to form the products. Some of the energy will be converted and dissipated as heat energy (more in the next paragraph). The point is that the energy for chemical reactions *already exists* in the universe before it is converted to another form of energy. The energy is never destroyed: it simply takes a different form.

For example, when you eat breakfast and run for the bus to come to class, you are transforming the **potential energy** in the food that you have eaten into kinetic energy while running for the bus. Inside of your cells, chemical reactions rearrange the matter in the food you eat to release the potential energy from those molecules and your muscle cells convert the energy released into kinetic energy (running). However, energy transformations are never 100% efficient. This means that you can never recover 100% of the potential energy stored in the food you eat to convert it to kinetic energy. This is an application of the **second law of thermodynamics**. A precise statement of the second law of thermodynamics is beyond the scope of this course. However, we can *apply it* to an understanding of energy transformation by stating that transformations of energy are never 100% efficient because some energy will be dissipated as heat energy. **Every single energy transformation or chemical reaction within and outside of cells will result in some of the energy invested or released to be converted into heat energ**y. The heat energy is not "lost" but it cannot be recovered or used to do additional work. This is not a good nor a bad thing: it is simply the way that our universe works!

Animals that maintain body temperatures different than their surroundings benefit from the second law of thermodynamics, including humans. When we convert the potential energy of food we have eaten into kinetic energy during muscle contraction, every single one of those chemical reactions dissipates some of the energy as heat. The released heat helps to maintain our internal body temperatures at a constant 37°C, regardless of the temperatures of our surroundings.

Activity: Drag and drop the correct type of energy described by the statements below. By doing so, you will be demonstrating the first law of thermodynamics as energy is transformed from one form to another by cells and organisms.

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Gradients and potentials

Recall: solutions are homogenous mixtures of a solute in a solvent. Sometimes solutes are found at uneven concentrations within a solution. The **concentration** of a solute in a solution is the amount of solute per volume, usually measured in moles per litre or **molarity** (M) or as the percent mass of solute per volume (%). If the concentration of a solute is non-uniform within a solution, this results in a **concentration gradient** within that solution. A **gradient** refers to a difference in the distribution of **matter** within a system.

Figure 13: Beaker containing a solution with a gradient of solute.

Concentration gradients are a form of **chemical potential energy**. This is because solutes tend to move from **high concentration to low concentration**. This phenomenon is known as **diffusion** and you will discuss it further in lab and lecture. Solutions move toward even mixing or **equilibrium**. Therefore, a concentration gradient within a solute represents a **chemical potential** where the molecules have the *potential* to move to an area of lower concentration within the solution. A **potential** refers to a difference in the distribution of **energy** within a system.

Recall that charged atoms are called ions. Ions form a chemical concentration gradient within a solution but they also bear charges. If the charge distribution within a solution is non-uniform, this results in an **electrical gradient.** Electrical gradients result in one part of the solution being more negatively charged and another part of the solution being more positively-charged. The resulting non-uniform distribution of charge is an **electrical potential** because negative charges tend to move toward areas of positive charge and vice versa. Ion gradients represent *both* a chemical concentration gradient AND an electrical gradient. The sum of these two gradients is collectively referred to as an **electrochemical gradient** and the difference in chemical and electrical energy within that system is called an **electrochemical potential.**

Electrochemical gradients and the resulting electrochemical potentials are biologically important. Cells actively maintain electrochemical gradients across their membranes to ensure that electrochemical signals can be sent from the brain, along nerves, to muscle and gland cells. Electrochemical gradients across cell membranes ensure that cells can generate energy. You will have a fuller understanding of these processes by the completion of this course.

Activity: A salt crystal containing ~10% salt concentration is dropped into different beakers containing saline solutions of varying concentrations. Select an arrow and drag and drop it to the correct position on the diagram below to show **what direction salt will move in solution**.

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Chemical reactions and chemical equilibrium

In a solution, **equilibrium** is the even mixing of solutes within a solvent. Solutes tend to move from areas of high concentration to areas of low concentration, leading to even dispersal of the solute in solution. Chemical reactions may also be in equilibrium. What does this mean?

Recall that chemical reactions can occur in two directions: forward and reverse. For example, the formation of carbonic acid is endergonic in the forward reaction and exergonic in the reverse reaction. **Chemical equilibrium** occurs when the forward reaction and the reverse reaction occur at the same rate. Special conditions are required to achieve chemical equilibrium for each reaction.

Inside of cells, most chemical reactions *do not* occur in conditions that favour chemical equilibrium. The special environment maintained within the cell ensures that some chemical reactions are **irreversible**, meaning that the reaction performed cannot convert the products back into the reactants. Most metabolic reactions are irreversible reactions. However, cells may **change** the **intracellular** environment to increase the rate of a reversible reaction in a particular direction. This is also true at the tissue, organ, and organ system level. For example, you will learn about how red blood cells, blood, and the respiratory system cooperate to ensure that carbon dioxide is effectively removed from the blood in a timely manner during our discussion of the respiratory system.

Cells change the conditions within the cell to affect whether certain chemical reactions will occur and how fast they will occur. This phenomenon is called **regulation** and you will examine this topic in nearly every lecture of this course.

Summary:

- Energy is the capacity to do work. It can be neither created nor destroyed and every energy transformation dissipates some energy as heat energy.
- A **gradient** is an uneven distribution of matter within a system.
- A **potential** is an uneven distribution of energy within a system.
- Cells use both chemical and electrical gradients, or **electrochemical gradients**, to store energy and prepare for the many energy transformations that sustain life.
- Chemical reactions rearrange matter
  - Endergonic chemical reactions require energy input to make/break bonds
  - Exergonic chemical reactions release energy as bonds are made/broken
- Chemical reactions achieve equilibrium when the **rate of the forward and reverse reactions are approximately the same**
  - The intracellular environment may favour one direction but the intracellular environment can change

Chapter 4 Quiz

Complete the following questions. Multiple choice and fill-in-the-blank questions will be scored to help you assess your progress. Good luck!

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CHAPTER 5: BIOLOGICAL MOLECULES

We have discussed the structure of atoms and molecules, as well as how atoms and molecules can be rearranged by chemical reactions. Many of the molecules and compounds we have been discussing are **inorganic compounds**, such as sodium chloride (NaCl) or molecular oxygen (O_2). These compounds do not contain the element carbon. Cells import and generate **organic compounds:** molecules containing carbon and synthesized by cells.

The structure of organic compounds is based on a chain of carbon atoms linked by covalent bonds known as a **carbon skeleton**. In the same way our bodies are framed by a skeleton, organic molecules are formed by a basic frame made of carbon chains. Recall that the valence number of carbon is four, meaning that carbon can form a maximum four covalent bonds with other atoms. Molecules that contain *only* carbon and hydrogen atoms are known as **hydrocarbons.** However, most organic compounds contain some combination of carbon, hydrogen, oxygen, and nitrogen. As a result, these atoms are the most abundant elements in cells. Other elements are less abundant in organic compounds (e.g. phosphorus and sulfur). Organic compounds synthesized and consumed by cells may also be referred to as **biological molecules**.

Cells contain trillions of biological molecules. However, all biological molecules are composed of relatively few subunits. Think of biological molecules like brick houses: the bricks are the building blocks or **monomers** from which all biological molecules are built. The many different types of brick houses are the **polymers** that differ by the arrangement of the bricks or monomers.

Biological monomers are incorporated one-at-a-time into larger molecules through a chemical process known as **dehydration synthesis**. Dehydration synthesis is the formation of covalent bonds between a growing biological polymer and an incoming biological monomer. A by-product of dehydration synthesis is a water molecule, hence the name "dehydration synthesis". Cellular enzymes perform dehydration synthesis to build cellular molecules. Cellular chemical reactions that **build** more complex molecules from smaller subunits are called **anabolic reactions.**

The reverse reaction is called **hydrolysis** and involves breakage of covalent bonds between monomers in a biological polymer. Reactions that break complex molecules into simpler subunits are called **catabolic reactions.** Cells perform hydrolysis reactions to release biological monomers for a variety of reasons. For example, during digestion of food, cells will catabolize large food particles into smaller nutrients that can be used to generate cellular energy or build new biological molecules that the cell needs to move, grow, and divide.

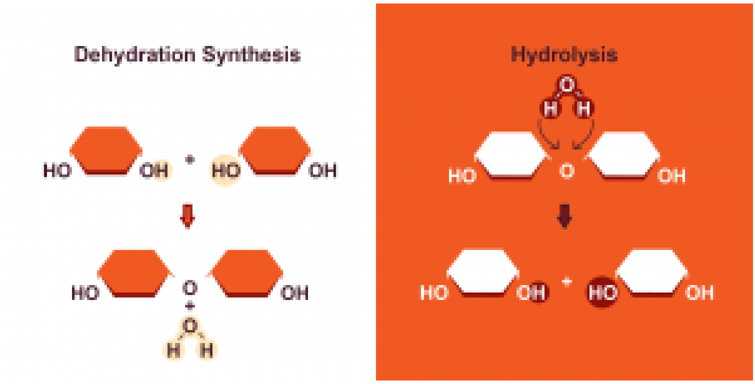

Figure 14. Dehydration synthesis and hydrolysis of a biological polymer.

There are four classes of biological molecules:

1. Carbohydrates
2. Proteins
3. Nucleic acids
4. Lipids

In this last chapter, we will examine the structure and function of each class of biological molecule.

Carbohydrates

Carbohydrates are a biological polymer made of monomers called **monosaccharides.** Monosaccharides are sometimes referred to as “simple sugars” because they are the building block for large, complex carbohydrates or sugars. Monosaccharides containing six carbons, or **hexose sugars**, include glucose, fructose, and galactose. The hexose sugars are the main fuels of cells, especially glucose. Monosaccharides containing five carbons, or **pentose sugars**, include ribose and deoxyribose. The pentose sugars are important components of nucleic acids such as deoxyribonucleic acid (DNA) and ribonucleic acid (RNA).

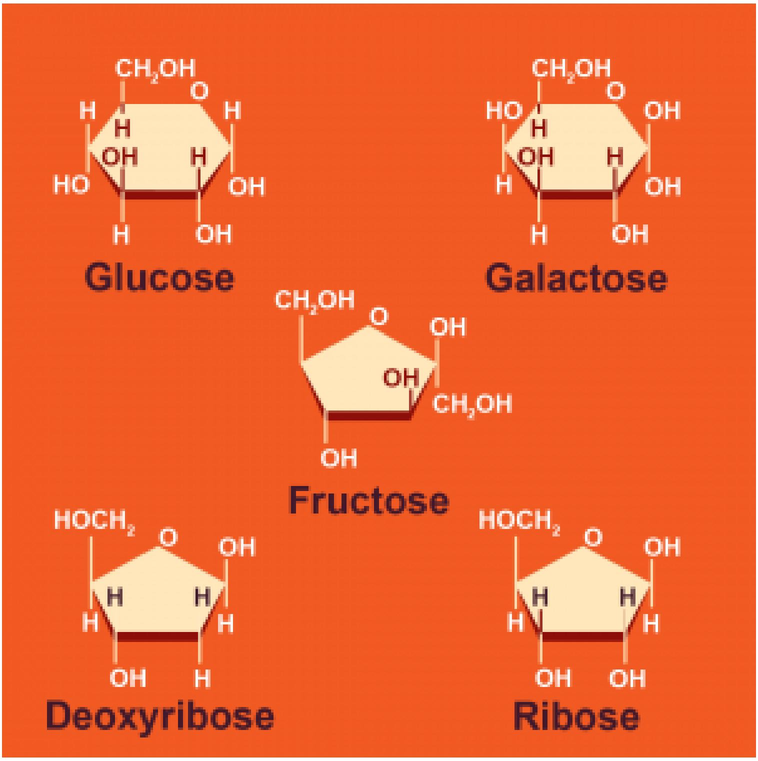

Figure 15. Chemical structures of monosaccharides, including glucose, fructose, galactose, ribose, and deoxyribose.

Carbohydrates are named based on the **length** of the polymer chain. Monosaccharides are the simplest carbohydrate and contain carbon, hydrogen, and oxygen in a ratio of 1:2:1. When two monosaccharides are covalently linked by dehydration synthesis, a water molecule is generated, and the resulting **disaccharide** *no longer contains a* C:H:O *ratio of* 1:2:1. The covalent bonds that link monosaccharides to one another and to other molecules is known as a **glycosidic bond**.

Three biologically important disaccharides are sucrose, maltose, and lactose. Sucrose is a polymer containing one glucose and one fructose sugar. Maltose is a polymer containing two glucose sugars. Lactose is a polymer containing one glucose and one galactose sugar.

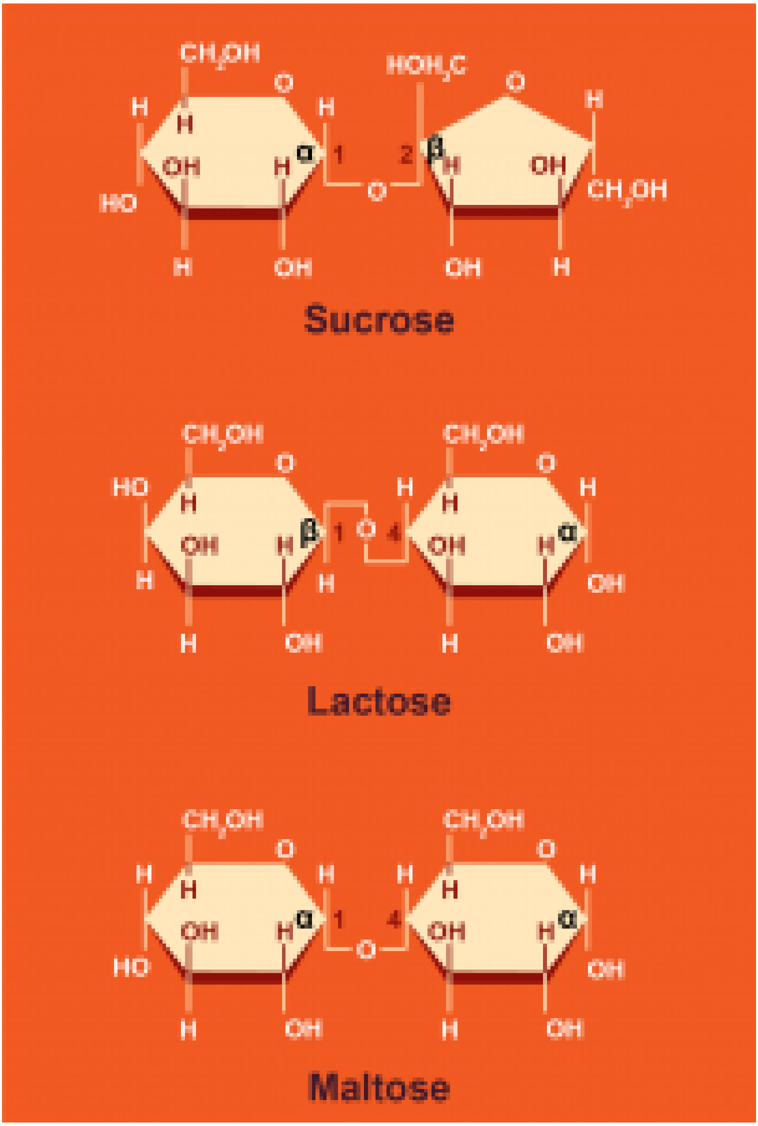

Figure 16. Chemical structures of sucrose, maltose, and lactose.

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Sucrose is simple table sugar and sweetens food. Maltose also lends sweetness to foods and beverages, such as beer. Lactose is a sugar found in dairy products such as milk and cheese.

Carbohydrates that consist of hundreds or thousands of monosaccharides are called **polysaccharides**. Polysaccharides play vital roles inside and outside of cells. Three biologically important polysaccharides include glycogen, starch, and cellulose. All three of the following polysaccharides consist *only* of glucose monomers linked by glycosidic bonds. However, the *arrangement* of glucose monomers differs between the polymers.

Glycogen consists of branched chains of glucose monomers linked by glycosidic bonds. Glycogen is only made in animal cells, such as human liver cells or **hepatocytes** and is the **storage polysaccharide** of animal cells. When human cells need energy, cellular enzymes hydrolyze the glycosidic bond between a glucose monomer and the rest of the chain to release glucose for energy processing reactions.

Starch is a long linear chain of glucose monomers linked by glycosidic bonds. The glycosidic bonds in starch and glycogen are identical but, unlike glycogen, starch is **unbranched**. Starch is synthesized by **plant cells** to store chemical potential energy. Therefore, starch is known as the **storage polysaccharide** of plant cells. When humans eat plants, the starch in those cells can be broken down by our digestive system to release glucose to our cells for energy processing reactions.

Cellulose, like starch, is a long linear chain of glucose monomers linked by glycosidic bonds. However, the glycosidic bond in cellulose is different from the glycosidic bond in starch and glycogen. Cellulose forms rigid **fibres** that support the structure of plant cells in a structure known as the **plant cell wall.** As a result, cellulose is known as the structural polysaccharide of plant cells and *cannot be made by human cells*. Human cells do not have the enzymes to hydrolyze the glycosidic bond in cellulose. Therefore, when we eat cellulose-rich plant foods, these materials travel nearly intact through our digestive systems and act as fibre to keep bowel movements regular.

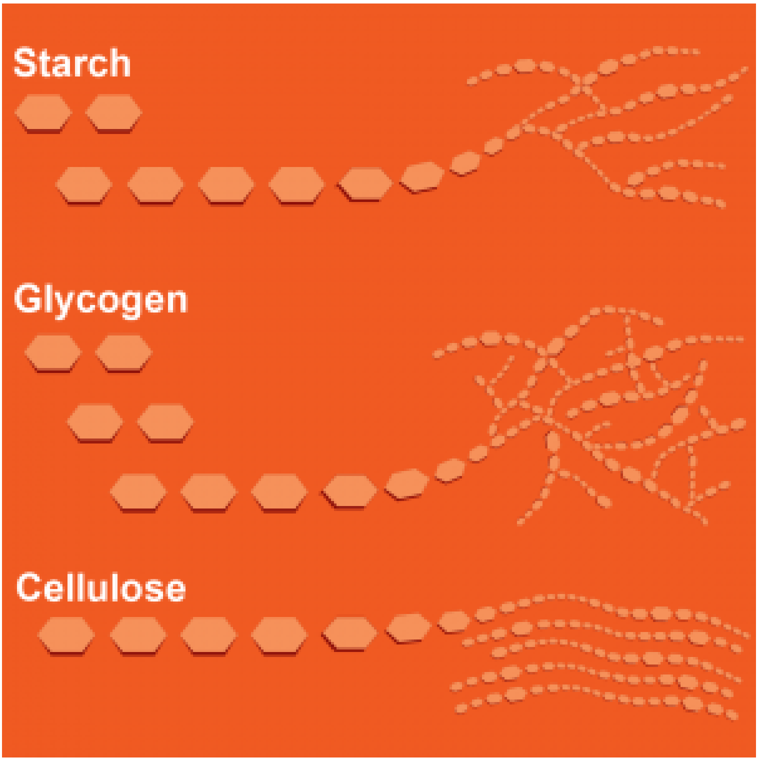

Figure 17. Chemical structures of starch, cellulose, glycogen.

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Proteins

Proteins are chains of amino acid monomers linked by covalent bonds called **peptide bonds** folded into a specific shape. The linear chain of amino acids may be referred to as a **peptide**. Chains with few amino acids (i.e. less than 50 amino acids) are called **oligopeptides**. Proteins that consist of multiple peptide chains are known as **polypeptides**. Some proteins consist of a single peptide chain. Some proteins consist of many peptides.

There are 20 naturally occurring amino acids. Every amino acid consists of a central carbon atom covalently bonded to four groups: a hydrogen, an amino group (-NH_2), a carboxyl group (-COOH), and a **reactivity or R group**. The R groups are unique to each amino acid. R groups may be nonpolar and hydrophobic, polar and hydrophilic, or charged and hydrophilic. When the amino acids are joined by dehydration synthesis into a growing peptide, the amino groups always face one direction, and the carboxyl groups always face the opposite direction. As a result, every protein has an **amino end or N-terminus** and a **carboxyl end or C-terminus**. The N-terminus is considered the "start" of the protein and the C-terminus is considered the "end".

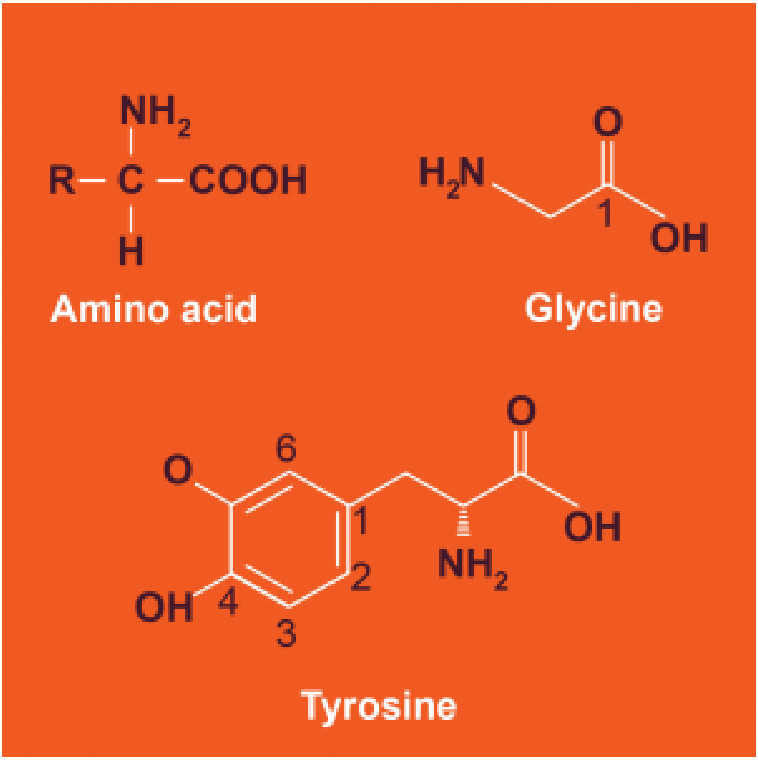

Figure 18. A. Chemical structure of amino acids and B. an oligopeptide.

Protein structure can be organized into four levels of complexity.

1. **Primary protein structure** is simply the order or sequence of amino acids within the peptide chain(s). The covalent peptide bond stabilizes primary protein structure.
2. **Secondary protein structure** is the formation of hydrogen bonds between amino acids within a peptide chain, forming either a coil called an **α-helix** or a flat structure called a **β-sheet**. Peptides may contain both types of secondary structural features or only one type.
3. **Tertiary protein structure** is the arrangement of the peptide

chains in space. For most proteins, hydrophobic interactions drive proteins to “hide” hydrophobic protein surfaces from the surrounding aqueous solution. However, hydrogen bonds and covalent bonds can also stabilize tertiary protein structure. For example, the amino acid cysteine contains a sulfhydryl group (-SH) that can form strong covalent bonds called **disulfide bonds** with another cysteine. Disulfide bonds are important to the tertiary structure of some proteins. In *all* proteins, tertiary structure is how the α-helices or a β-sheets *within single peptide chains* are arranged relative to one another in three-dimensional (3-D) space.

4. Finally, **quaternary protein structure** is the arrangement of different peptides relative to one another in 3-D space. Weak noncovalent interactions such as hydrogen bonds or strong covalent bonds such as disulfide bonds may stabilize quaternary protein structure, depending on the amino acid sequence of that protein. Importantly, not all proteins have quaternary protein structure because some peptides consist of only one peptide chain. In proteins that are only a single peptide chain, the highest level of protein structure these proteins achieve is tertiary protein structure.

Let us examine the different levels of protein structure in a human protein. **Hemoglobin** is a protein synthesized by red blood cells that binds and transports oxygen in blood. Hemoglobin is a polypeptide consisting of four peptides: two identical **α-globin peptides** and two identical **β-globin peptides**. The α- and β-globin peptides differ in **primary structure** or amino acid sequence. Both globins are mostly α-helical proteins and, therefore, have similar secondary structures. Each globin folds in a unique manner dictated by the chemical nature of the amino acids within each peptide. However, both globin subunits must fold to accommodate an iron-containing **heme group** that contains the oxygen-binding site. The folding of each globin into a shape that is covalently bound to heme is the **tertiary structure** of each peptide. Because hemoglobin is a polypeptide, this protein has quaternary structure. The quaternary structure of hemoglobin is the arrangement of the four globin molecules in space.

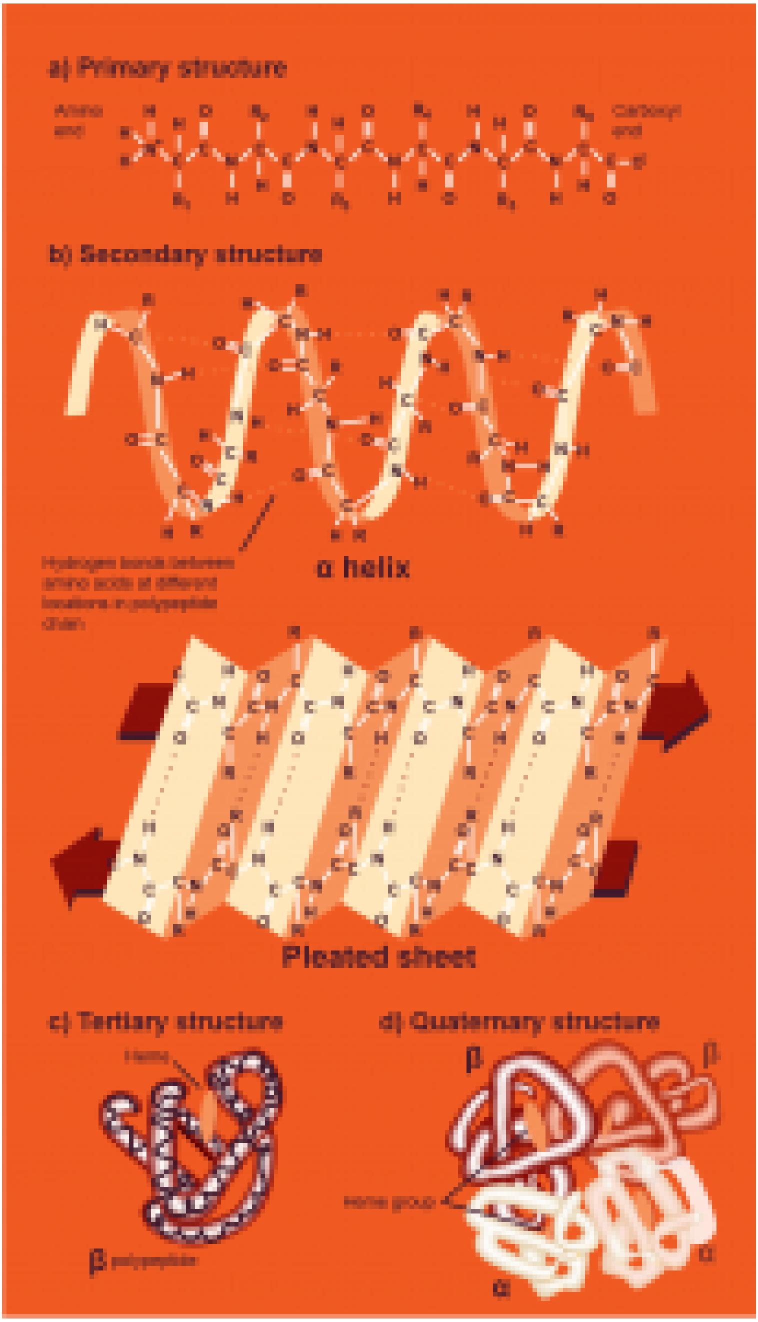
a) Primary structure
Amino end
Carboxyl end
b) Secondary structure
Hydrogen bonds between amino acids at different locations in polypeptide chain
α helix
Pleated sheet
c) Tertiary structure
Heme
β polypeptide
d) Quaternary structure
β
β
Heme group
α
α

Figure 19. The structural organization of hemoglobin.

The structure of proteins determines their function. For example, the function of hemoglobin is to transport oxygen in blood. This function is only possible because the tertiary structure of hemoglobin permits oxygen-binding to occur at the covalently bound heme molecule. Additionally, because each hemoglobin protein can bind a maximum of **four** oxygen molecules, this permits a large volume of oxygen to be transported in hemoglobin at a time. The shape of proteins determines what molecules the protein can interact with, including other proteins. The final shape or fold of a protein that permits cellular function is known as the protein's **native fold.**

Changes to environmental conditions can alter protein folding and, therefore, protein function. For example, changes to the pH of the surrounding solution can disrupt the hydrogen bonds that stabilize secondary, tertiary, and/or quaternary protein structure. When the native fold of proteins is lost or disrupted, proteins are **denatured**. Denatured proteins are biologically **inactive** because they can no longer interact with other cellular molecules due to their altered structure. Note that the *peptide bonds* that link amino acids within denatured proteins remains intact.

Proteins are diverse molecules in cells that perform many cellular functions. Recall that **enzymes** are proteins that can perform chemical reactions. All the reactions that help extract energy from food we digest in the small intestine are performed by cellular enzymes. Protective structures such as hair and nails consist of an abundant protein called **keratin**. Keratin is a **fibrous protein**, meaning it forms an extended thread-like structure that is not soluble in water. In contrast, the protein hemoglobin is a **globular protein**, meaning it forms a compact structure that is generally soluble in water. Proteins are also found protruding from cell membranes as **receptors** for signals such as hormones or neurotransmitters. Proteins embedded in cell membranes that move ions across the cell membrane permit nerve and muscle cells to send and receive signals, respectively. Clearly, proteins perform critical cellular functions and this is only possible because of their unique structures.

Nucleic Acids

Nucleic acids are biological polymers of a monomer called **nucleotides**. Nucleotides consist of a pentose sugar covalently bound to a negatively charged phosphate and a nitrogenous base. There are five common nitrogenous bases: adenine (A), thymine (T), guanine (G), cytosine (C), and uracil (U). When nucleotides are incorporated into a growing nucleic acid by dehydration synthesis, the sugar-phosphates of adjacent nucleotides are linked by covalent bonds called **phosphodiester bonds**.

Two biologically important nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. DNA and RNA are both important nucleic acids in cells, but they differ by several structural characteristics. First, the pentose sugar of all nucleotides that comprise DNA is **deoxyribose** while the pentose sugar of all nucleotides that comprise RNA is **ribose**. Second, DNA contains only A, T, G, and C; RNA contains only A, U, G, and C. Third, DNA is **double-stranded**. This means that one chain of nucleotides always pairs with a second chain of nucleotides to form a unique **double helix**. In contrast, RNA is generally **single-stranded**, meaning one chain of nucleotides folds on itself.

Chemistry in the clinic:

The double helical structure of DNA was determined by an X-ray crystallographer named Rosalind Franklin and published by her colleagues James Watson and Francis Crick. Watson, Crick, and Franklin's supervisor Maurice Wilkins received the Nobel Prize in Physiology or Medicine in 1962 for their discovery of the double helical structure of DNA. Franklin died due to complications from ovarian cancer in 1958 and did not share in the Nobel Prize for her contribution to the discovery of DNA structure. The double helical structure of DNA was essential to understanding how DNA copies itself or **replicates** and how other cellular molecules such as proteins interact with DNA.

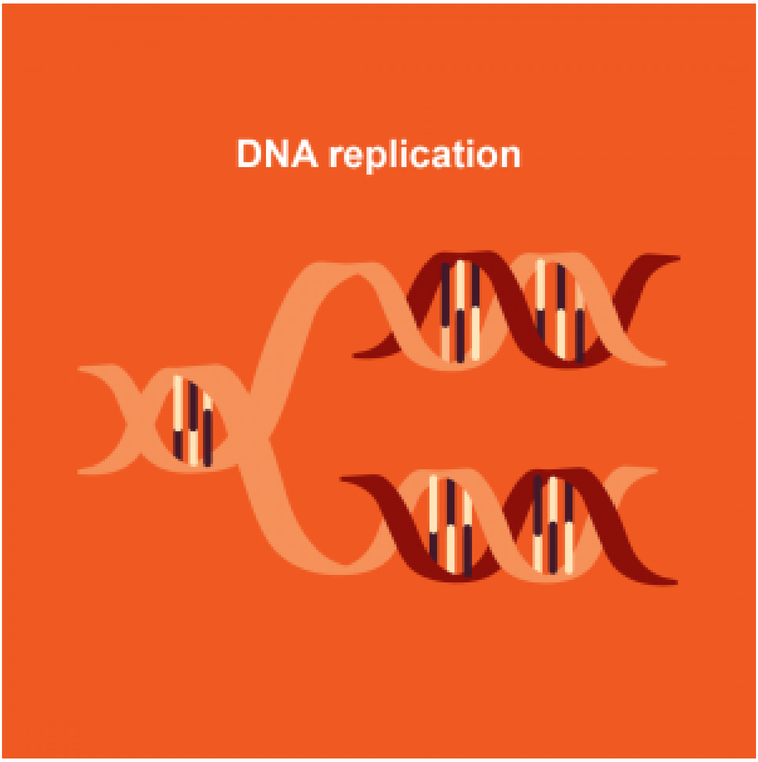

Figure 20. The DNA double helix and semi-conservative DNA replication.

The DNA double helix consists of two nucleotide chains or strands that face opposite directions. The **antiparallel** arrangement of DNA strands is stabilized by chemical bonds that link the nitrogenous bases of adjacent strands together. Think of the DNA double helix as a winding staircase: the sugar-phosphate portions of the nucleotides form the "rails" while the nitrogenous bases face inward toward one another and form the “stairs”. The nitrogenous bases pair in a specific manner: A always pairs with T and G always pairs with C. These nitrogenous bases are held together by hydrogen bonds. The discovery of the double helical structure of DNA helped scientists answer an important question: how DNA was copied or **replicated**.

The function of DNA is to provide instructions to cells on how to build that exact same cell. Before cells divide, they must **replicate** their DNA so that the daughter cell receives a full copy of the genetic instructions. During DNA replication, the DNA double helix is *unwound* and the hydrogen bonds between base pairs is disrupted. Each strand serves as a **template** for cellular enzymes to create a **complementary** strand of DNA. Complementary strands do not have the same sequence as the template. Instead, cellular enzymes use the pairing rules of nitrogenous bases to complete a new daughter strand of DNA: if the template strand contains an A base, then enzymes will insert a T in the new molecule. If the template strand contains a G, then enzymes will insert a C in the new strand. As a result, each resulting daughter molecule from DNA replication contains one “old” template strand and one “new” strand. This type of DNA replication is known as **semi-conservative DNA replication**. Understanding the double helical structure of DNA provided scientists with a clue as to how semi-conservative DNA replication proceeds.

Short DNA sequences that provide instructions for the cell to make a protein are called **genes**. In human cells, genes are **transcribed** by enzymes into a special set of RNA molecules called **messenger RNA** (mRNA) in the cell nucleus. The mRNA exits the nucleus and is bound by molecular machines called **ribosomes** in the cytosol or on the rough endoplasmic reticulum. You will examine these **organelles** in a later unit of the course. **Translation** of mRNA into peptides by ribosomes produces a protein. The sequence of nucleotides in genes determines the mRNA sequence and, therefore, the **amino acid sequence of the encoded protein.** Changes to the identity of nucleotides within a DNA sequence are called **mutations**. Mutations in DNA may change the amino acid sequence of proteins, resulting in different protein function. This flow of information within cells from the DNA of genes through an mRNA intermediate to a translated protein is known as the **central dogma of biology**.

RNA, therefore, functions as a transcript of the protein-encoding messages in genes. RNA also forms a part of ribosomes (**ribosomal RNA or rRNA)** and molecules that bring amino acids to ribosomes to assist with mRNA translation (**transfer RNA or tRNA).**

Together, the nucleic acids of the cell — DNA and RNA — provide the cell with instructions to make proteins and those proteins determine the characteristics and functions of the cell.

Activity: Using your knowledge of the central dogma, type in the correct mRNA sequence given the DNA sequence below. Once you have determined the mRNA transcript sequence, use the codon table given below to translate the mRNA into protein.

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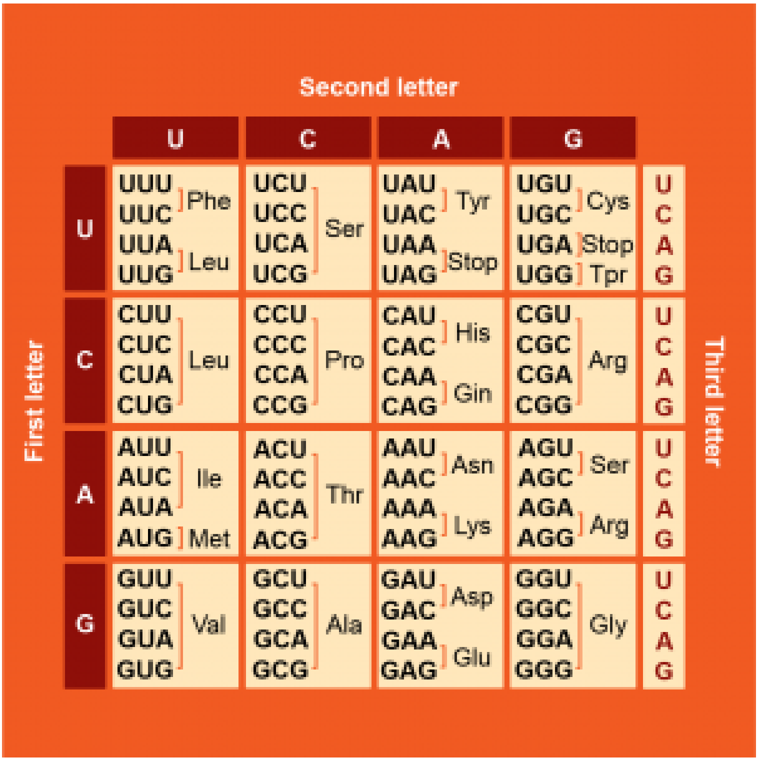

	Second letter								
First letter	U		C		A		G		Third letter
U	UUU	Phe	UCU	Ser	UAU	Tyr	UGU	Cys	U
	UUC		UCC		UAC		UGC		C
	UUA	Leu	UCA		UAA	Stop	UGA	Stop	A
	UUG		UCG		UAG		UGG	Tpr	G
C	CUU	Leu	CCU	Pro	CAU	His	CGU	Arg	U
	CUC		CCC		CAC		CGC		C
	CUA		CCA		CAA	Gln	CGA		A
	CUG		CCG		CAG		CGG		G
A	AUU	Ile	ACU	Thr	AAU	Asn	AGU	Ser	U
	AUC		ACC		AAC		AGC		C
	AUA		ACA		AAA	Lys	AGA	Arg	A
	AUG	Met	ACG		AAG		AGG		G
G	GUU	Val	GCU	Ala	GAU	Asp	GGU	Gly	U
	GUC		GCC		GAC		GGC		C
	GUA		GCA		GAA	Glu	GGA		A
	GUG		GCG		GAG		GGG		G

Codon Table

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Adenosine triphosphate (ATP)

One biologically important nucleotide that is not incorporated into DNA or RNA is adenosine triphosphate or ATP. ATP is a nucleotide because it consists of the pentose sugar ribose, the nitrogenous base adenine, and three phosphate groups. ATP is a form of energy currency within cells. When cells perform exergonic, catabolic reactions, the energy released is stored as chemical potential energy in ATP. When cells are ready to use that energy to perform endergonic, anabolic reactions, the energy is released from ATP by **hydrolyzing the bonds in ATP molecules**.

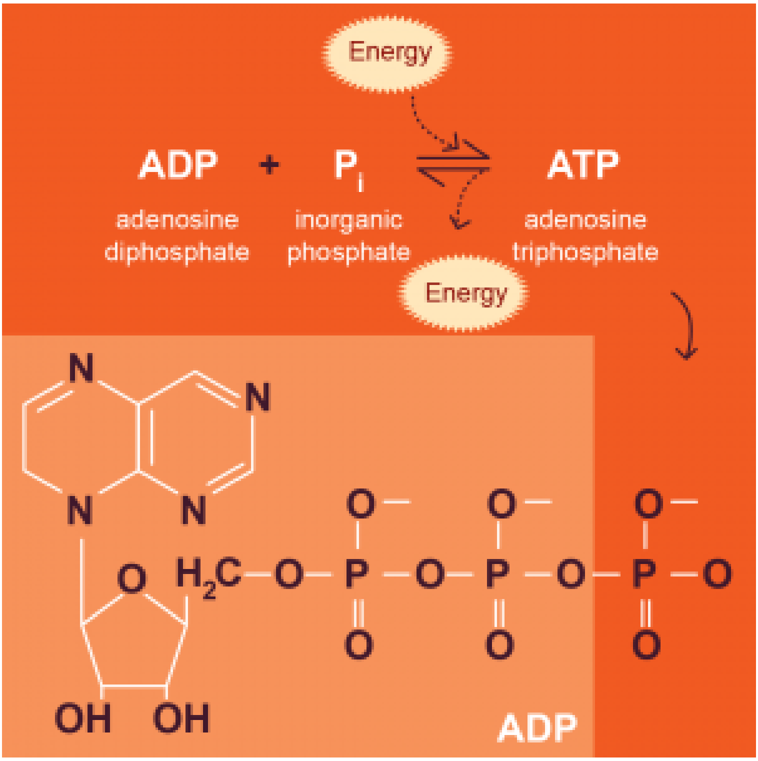


Figure 21: ATP synthesis and hydrolysis in dynamic equilibrium.

Lipids

The last class of biological molecules are the **lipids. Lipids are not considered biological polymers** because the diverse structures of lipids do not contain a single identifiable monomer. In other words, there is no single building block that appears to be a part of all types of lipids. However, all lipids consist of carbon, hydrogen, and a very small proportion of oxygen. Due to the numerous nonpolar covalent bonds that comprise lipids, lipids are generally considered hydrophobic.

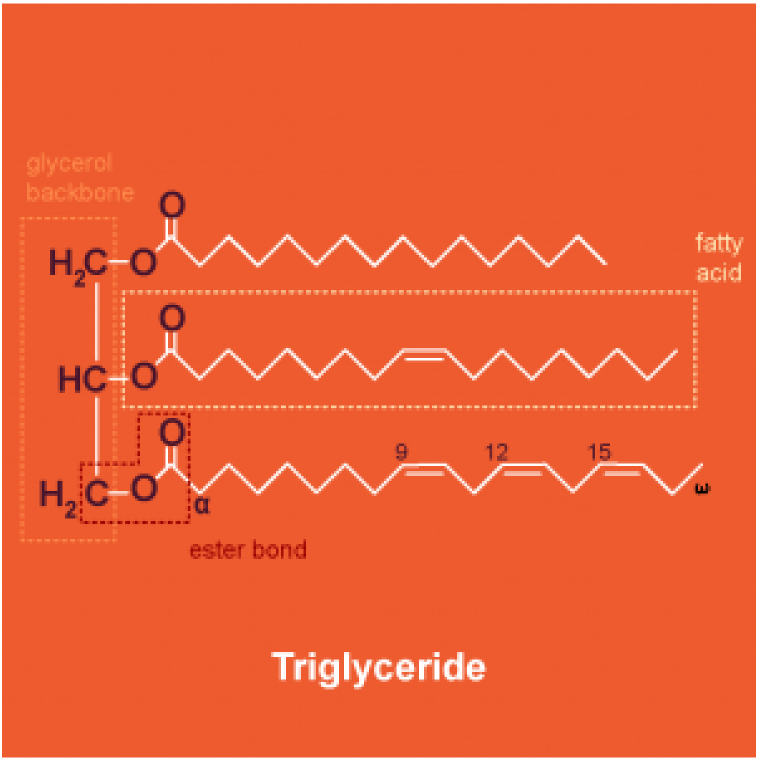
Many cellular lipids contain molecules known as **fatty acids:** extended hydrocarbon chains with a carboxyl group (-COOH) at one end. The hydrocarbon chains of fatty acids are nonpolar and hydrophobic. Fatty acids that contain only single carbon-carbon (C-C) bonds are called **saturated fatty acids** because all carbons form the maximum number of bonds to hydrogen. Saturated fatty acids tend to have a straight 3-D shape. Fatty acids that contain at least one double C-C bond are called **unsaturated fatty acids**. The double bonds in unsaturated fatty acids cause the hydrocarbon chain to bond or "kink".

Triglycerides

Triglycerides (also known as triacylglycerols or simply "fats") consist of a three-carbon molecule called glycerol covalently bound to three fatty acids. The covalent bond formed between the carboxyl groups of the fatty acids and the glycerol molecule is called an **ester bond**.

Triglycerides can be broken down in cells to release energy that the cell can harness for other cellular functions. As a result, one function of triglycerides is to store energy. Triglycerides store more energy per mass than carbohydrates (e.g. glycogen). Triglycerides are also stored in the cells of **adipose tissue** and function to insulate the human body from heat loss and protect the internal organs from injury.

Triglycerides are also consumed by humans. **Saturated fats** are triglycerides that contain saturated fatty acids. Saturated fats are generally solid at room temperature (e.g. butter). **Unsaturated fats** are triglycerides that contain at least one unsaturated fatty acid and are generally liquid at room temperature (e.g. olive oil). Because all fats contain large amounts of energy, the recommended daily intake of all fats is relatively small in proportion to carbohydrates and proteins.



Phospholipids

Phospholipids consist of a glycerol molecule covalently bound to two fatty acid molecules. The third carbon of glycerol is bound to a negatively charged phosphate group. The phosphate group may be covalently bound to an additional polar or charged chemical group. The charged and polar portion of phospholipids is hydrophilic and often referred to as the “head” of the molecule. The nonpolar and hydrophobic fatty acids are referred to as the “tails”. Molecules like phospholipids with a hydrophilic portion and hydrophobic portion are called **amphipathic.**

Phospholipids spontaneously assemble into special structures due to their amphipathic nature. One biologically important structure is the **phospholipid bilayer**. The hydrophilic heads of the lipids interact well with the surrounding aqueous solution, but the fatty acid tails interact best with one another. Therefore, phospholipids in aqueous solution may spontaneously form two layers. In each layer, the hydrophilic heads face outward toward the solution and the hydrophobic tails face inward, toward one another. Phospholipid bilayers serve as a scaffold for biological membranes, which you will learn about in lecture.

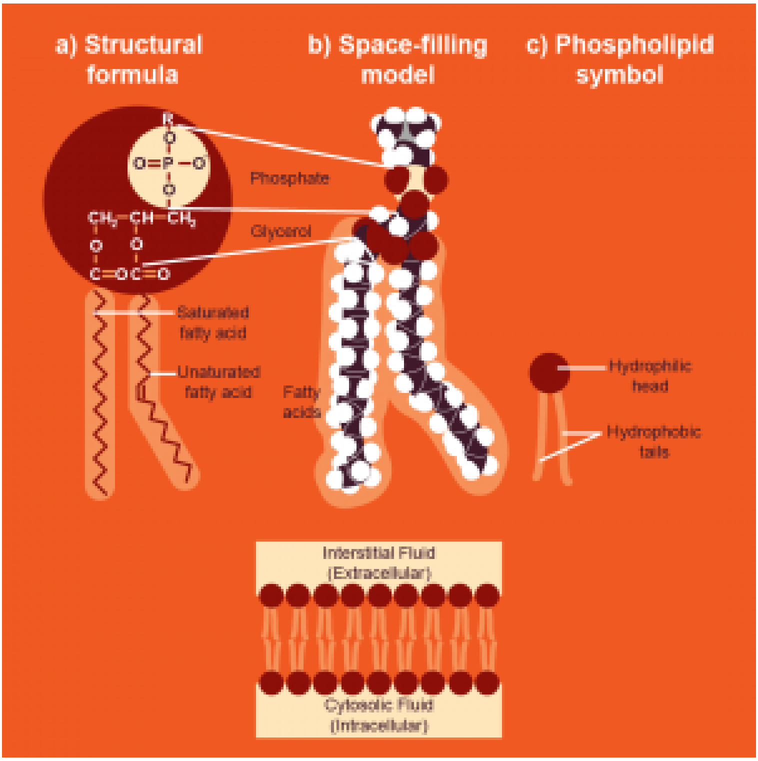


Figure 23. Chemical structure of a phospholipid and a lipid bilayer.

Steroids

Steroids, unlike triglycerides and phospholipids, consist of four fused carbon rings and other chemical groups. In humans, **cholesterol** serves many important cellular roles. Cholesterol consists of four carbon rings, plus a polar hydroxyl group (-OH) covalently bound to one ring and a short hydrocarbon chain covalently bound to another ring. As a result of the single hydroxyl group, cholesterol is weakly amphipathic. The **steroid hormones**, including the sex hormones testosterone and estrogen that determine the secondary sexual characteristics of humans, are made from cholesterol as a precursor. Cells also synthesize vitamins such as vitamin D from cholesterol precursors. Cholesterol is found in cell membranes: the polar hydroxyl group interacts with the hydrophilic phosphate heads of phospholipids. The nonpolar carbon rings and hydrocarbon chain interacts with the hydrophobic fatty acid tails of the phospholipids. You will discuss how cholesterol regulates membrane fluidity in lecture.

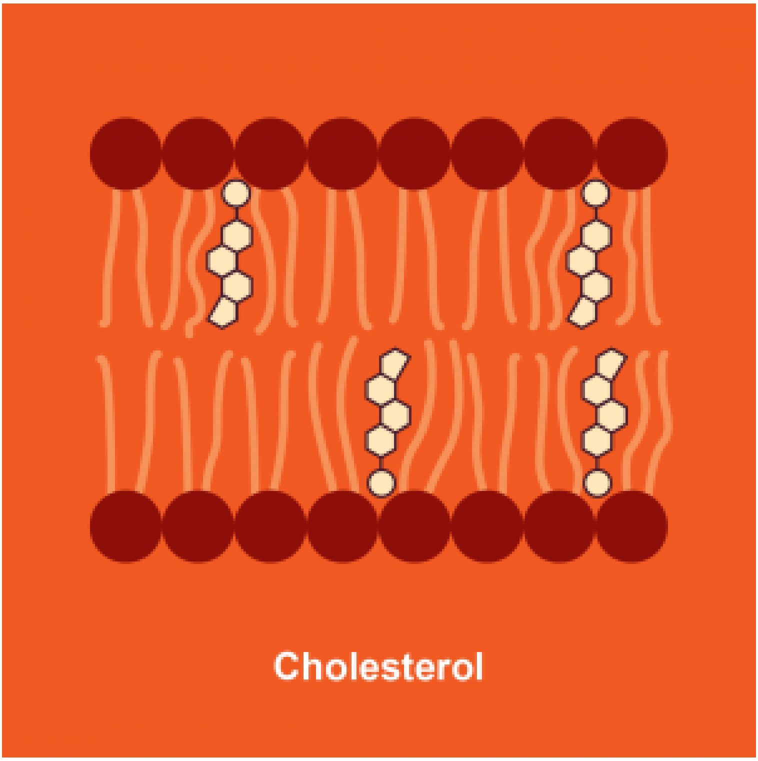


Figure 24. Chemical structure of cholesterol and cholesterol in a lipid bilayer.

Eicosanoids and leukotrienes

Eicosanoids are lipids that consist of 20-carbons with structures that resemble fatty acids . Eicosanoids are important signaling molecules within and between cells. **Leukotrienes** are a type of eicosanoid that specifically functions as part of an immune response to tissue damage called **inflammation**. Eicosanoids and leukotrienes serve as signals that help white blood cells detect, respond, and repair tissue damage that results from infection or invasion. You will discuss the functions of these molecules later in lecture and, perhaps, in future courses.

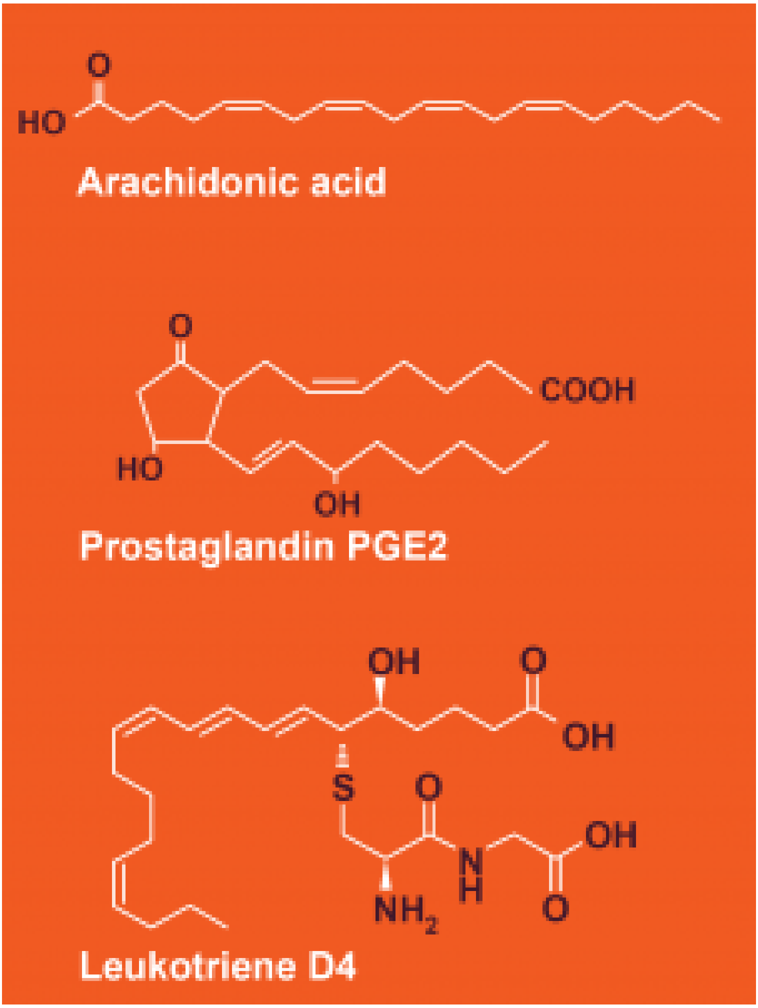


Figure 25. Chemical structures of arachidonic acid (an eicosanoid) + leukotriene D4.

There are many other types of lipids but, from the small subset covered by this course, you can see that lipids serve many cellular functions. Lipids form important structural components of cell membranes, store energy, insulate and protect the body, serve as hormones, and help immune cells send and receive signals during tissue damage.

Together, the four classes of biological molecules make up all the organic molecules in cells. Throughout Biology 1190, you will see examples of how the structures of these molecules specializes them for their unique and vital cellular functions. The understanding of basic chemical principles that shape molecules and the interactions between molecules is a critical part of your understanding of cellular and, therefore, human body function.

Summary:

- There are four classes of biological molecules:
  - Carbohydrates are polar and hydrophilic chains of monosaccharides
    - Monosaccharides such as glucose are the main cellular fuel
    - Disaccharides sweeten foods and beverages
    - Polysaccharides store energy in plant and animal cells and form part of the rigid plant cell wall
  - Proteins are diverse molecules that perform many functions for the cell
    - Proteins are chains of amino acids
    - Protein structure can be organized into four hierarchical levels
    - The structure of proteins determines their function
    - Conditions that denature proteins also eliminate protein function
  - Nucleic acids encode genetic information in cells
    - Nucleic acids are polymers of nucleotides
    - Genes are short sequences of DNA
    - Genes are transcribed to mRNA and mRNA is

    - translated to proteins
    - The structure of DNA is related to how it is replicated and transcribed
  - Lipids are diverse molecules that are not considered biological polymers
    - Triglycerides store energy, insulate, and protect the body from injury
    - Phospholipids are a structural component of biological membranes
    - Cholesterol is a weakly amphipathic component of biological membranes
    - Eicosanoids and leukotrienes are important signalling molecules between and within cells of the immune system

Chapter 5 Quiz - Part 1

Complete the following questions to practice and apply your knowledge from this chapter. Written responses will **not** be scored but you can mark your own responses using the solutions provided. Multiple choice and fill-in-the-blank questions will be scored to help you assess your progress. Good luck!

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Define each of the following terms:

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Chapter 5 Quiz - Part 2

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FINAL ASSESSMENT INSTRUCTIONS

To successfully complete Biology 1190, we recommend you score at least 80% on this final chemistry assessment. If you have remaining questions after completing this module, **please see your Biology 1190 instructor** for additional help and resources.

Good luck!!!

Final Assessment

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