

BIOLOGY FOR ENGINEERS

LECTURE NOTES

CO1

The basic elements and their bonding ability, macromolecules and their structures and their role and general law of thermodynamics in biological systems.

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Introduction to the course

Purpose of Biology for Engineers

“As engineers, we are always looking into how to modify or improve an existing system. We must hold the key to combining the fields of engineering and biology, and this course is designed to provide a logical understanding about biology from an engineering perspective. So our aim is to understand the logical principles of biology, inspire the ideas from it to have a useful creativity in the engineering field”

Elements of Life, Explanation about the important elements in any organism.

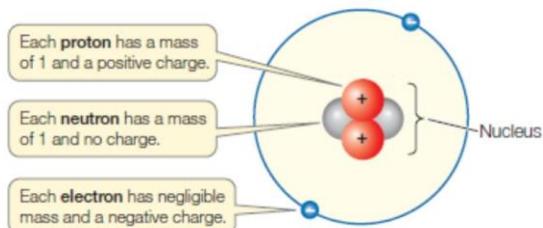
Electronegativity of the element, Importance of carbon.

Chemistry of life:

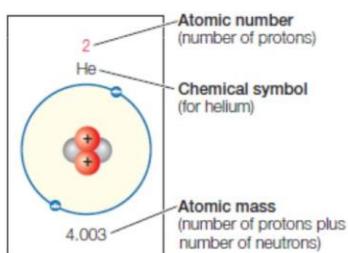
The atomic composition of the cell: H = 63%, O = 24% C = 10%, N = 1.4 %, P = 0.2 % & S = < 0.1%

Trace amount: Ca, Cl, K, Na, Mg, Mn, Fe, Se, I etc

Let us understand what an element is and where these elements related to life are present in the periodic table by simple pictures.



2.1 The Helium Atom This representation of a helium atom is called a Bohr model. It exaggerates the space occupied by the nucleus. In reality, although the nucleus accounts for virtually all of the atomic mass, it occupies only about 1/10,000 of the atom's volume. The Bohr model is also inaccurate in that it represents the electron as a discrete particle in a defined orbit around the nucleus.



2.2 The Periodic Table The periodic table groups the elements according to their physical and chemical properties. Elements 1–92 occur in nature; elements with atomic numbers above 92 were created in the laboratory.

1 H 1.0079	4 Be 9.012													2 He 4.003			
3 Li 6.941	4 Be 9.012	Elements in the same vertical columns have similar properties because they have the same number of electrons in their outermost shell.															
11 Na 22.990	12 Mg 24.305	Elements highlighted in orange are present in small amounts in many organisms.															
19 K 39.098	20 Ca 40.08	21 Sc 44.956	22 Ti 47.88	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.847	27 Co 58.933	28 Ni 58.69	29 Cu 63.546	30 Zn 65.38	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
37 Rb 85.4778	38 Sr 87.62	39 Y 88.906	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.906	46 Pd 106.4	47 Ag 107.870	48 Cd 112.41	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
55 Cs 132.905	56 Ba 137.34	71 Lu 174.97	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.2	78 Pt 195.08	79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (260)	103 Lr (260)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (269)	108 Hs (268)	109 Mt (269)	110 (269)	111 (272)	112 (277)	113 (285)	114 (289)	115 (289)	116 (289)	117 (293)	118 (293)
Masses in parentheses indicate unstable elements that decay rapidly to form other elements.															Elements without a chemical symbol are as yet unnamed.		
Lanthanide series																	
57 La 138.906	58 Ce 140.12	59 Pr 140.9077	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.924	66 Dy 162.50	67 Ho 164.930	68 Er 167.26	69 Tm 168.934	70 Yb 173.04				
89 Ac 227.028	90 Th 232.038	91 Pa 231.0359	92 U 238.02	93 Np 237.0482	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)				

When we look at the composition of elements, C, N, O & H constitutes more than 95%. They are also lightest elements in the periodic table (As we go down in the periodic table, atomic number is going to increase so as atomic mass)

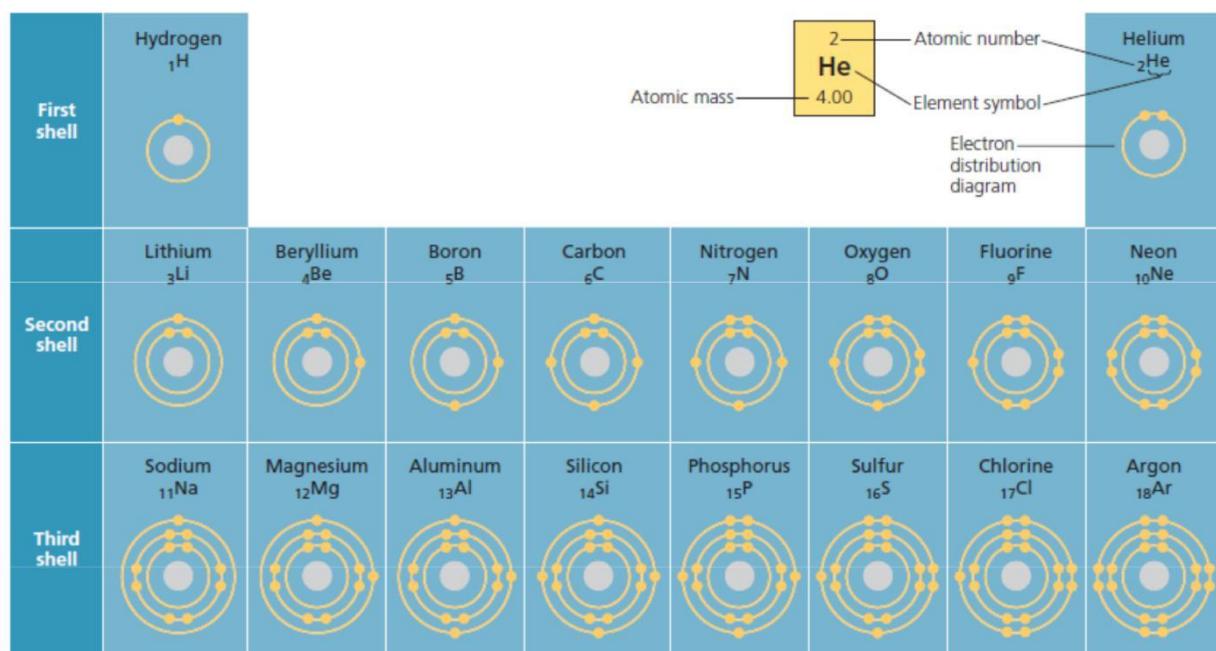
Suppose we want to design a moving machine like car what are the critical things we look for before selecting material to construct a body of the car? One of the criteria should be Materials used should not be heavy (fuel efficiency is going to decrease). The backbone element of life is carbon and carbon is the appropriate element to become a backbone element of life, since no element is present above carbon in periodic table which can have similar properties and lighter than carbon.

Important properties of these elements are their ability to form bond with other elements to form compounds/molecules. Let us see the molecular composition of the life. 80% is water & the dry weight of remaining 20% contains 50% protein, 15% carbohydrates, 10% lipids & fats & 15% nucleic acids.

Formation of these molecules and the interaction between these molecules depends on the chemical properties of the important six elements we mentioned it before. In this course, we just

learn Chemistry to logically understand the structure and functions of Biomolecules and their interaction.

Two important properties we are concentrating in this course to understand the elements used in life are valency and electronegativity. The Valency of an atom is unpaired electron in the outer orbital of the shell. This gives an opportunity for the element to combine with other element.



▲ Figure 2.9 Electron distribution diagrams for the first 18 elements in the periodic table. In a standard periodic table (see Appendix B), information for each element is presented as shown for helium in the inset. In the diagrams in this table, electrons are represented as yellow dots and electron

shells as concentric circles. These diagrams are a convenient way to picture the distribution of an atom's electrons among its electron shells, but these simplified models do not accurately represent the shape of the atom or the location of its electrons. The elements are arranged in rows, each representing the filling of an

electron shell. As electrons are added, they occupy the lowest available shell.

? *What is the atomic number of magnesium? How many protons and electrons does it have? How many electron shells? How many valence electrons?*

Valency of H = 1, C=4, O = 2, N = 3 or 4, P = 3 or 5 and S = 2 (As shown in the figure), 4, 6

Covalent Bond: sharing of a pair of valence electrons by two similar or dissimilar elements.

C–C single bond. Energy required to break them is equal to 80 Kcal/mol

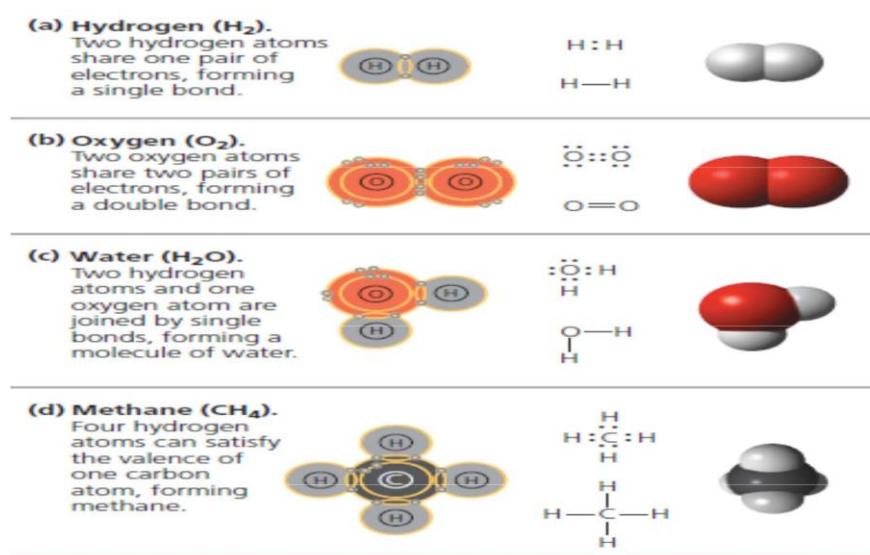
C=C double bond (more energy is required to break them compared to single bond between them)

C≡C triple bond (more energy is required to break them compared to double bond)

Covalent bonds are very strong. Suppose if we compare covalent bond strength to say random energy fluctuation in daily life- random thermal fluctuations at room temperature are on the order of 0.6 kilocalories per mole. Covalent bonds are extremely stable, usually, unless something is attacking them and breaking them.

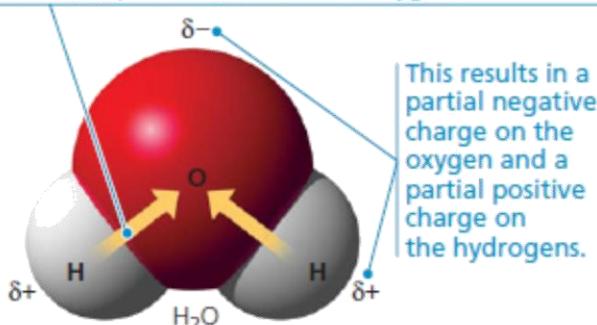
Different types of bonds, Some examples of different types of bonding in the biological systems, Water & phospholipid their importance in existence of life

Atoms in a molecule attract shared electrons in varying degrees, depending on the element. The attraction of a particular element for the electrons of a covalent bond is called its electronegativity. The more electronegative this element is, the more strongly it pulls shared electrons towards itself. If an element bonded to more electronegative element, the electrons of the bond are not shared equally therefore, There exists a polarity between them. This type of bond is called polar covalent bond. Such bonds vary in their polarity depending on the relative electronegativity of the two elements. For example the bond between the hydrogen atom and oxygen atom in water molecule is quite polar.



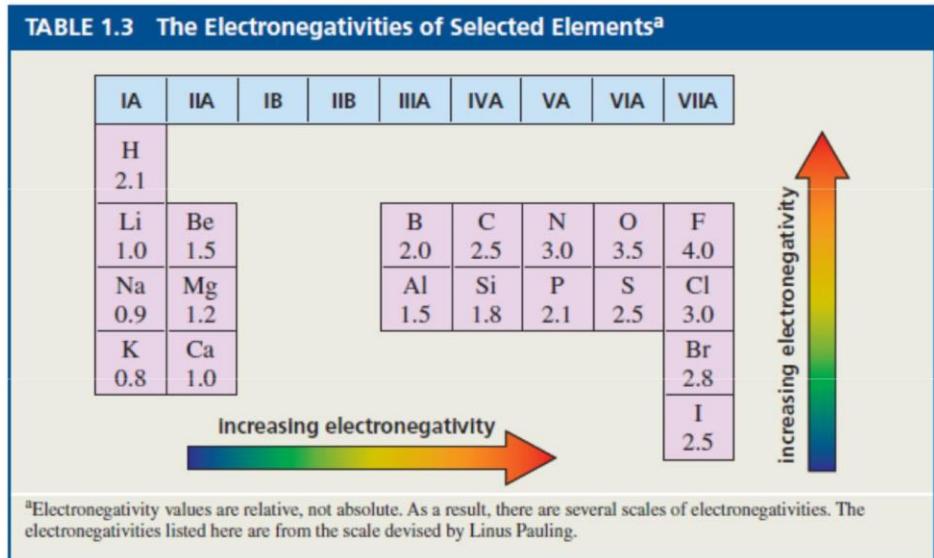
▲ **Figure 2.12 Covalent bonding in four molecules.** The number of electrons required to complete an atom's valence shell generally determines how many covalent bonds that atom will form. This figure shows several ways of indicating covalent bonds.

Because oxygen (O) is more electronegative than hydrogen (H), shared electrons are pulled more toward oxygen.



▲ **Figure 2.13 Polar covalent bonds in a water molecule.**

How do we know that polarity exist between two atoms of elements? What is the measuring way?



Please refer the figure above. Suppose if the difference in electronegativity between the two atoms is 0.5 and more, there exist polarity.

Example: carbon and hydrogen C-H the difference in electronegativity is 0.4 so it is non-polar. Carbon and oxygen C-O The difference is 1.0 therefore polarity exist.

Ionic Bond: transfer of electrons from one atom to another atom to form bond. The atom should form ions i.e. it should be in ionic state (positively charged or negatively charged) before it forms bond with another oppositely charged ion. The bonds are strong as long as it is not disturbed. If it is disturbed it becomes fragile. Ex: Once the water is added to NaCl, the ionic bond breaks.

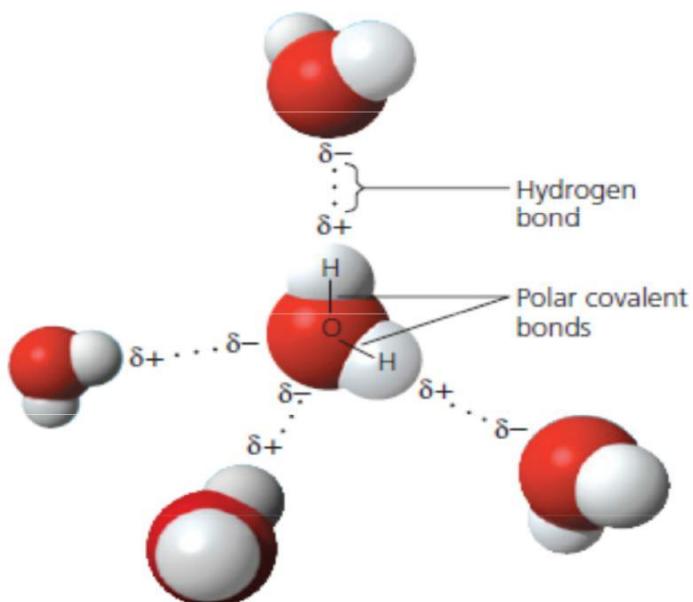
Water and Phospholipid

Life on earth began in water and evolved there for three billion years before spreading onto land. Although most of the water in liquid form, it is also in solid form and gaseous form.

Water is the only solvent, it is present in all the three phases and interchange of the phases will enormously affect the life on the earth. We look into some of the important properties of water that make earth suitable for life.

Polar covalent bonds in water molecules results in hydrogen bonding

The hydrogen bonds form, break and re-form with great frequency. Each lasts only a few trillionths of a second, but the molecules are constantly forming new hydrogen bonds with a succession of partners. Therefore at any instant, all water molecules are hydrogen bonded to their neighbours.

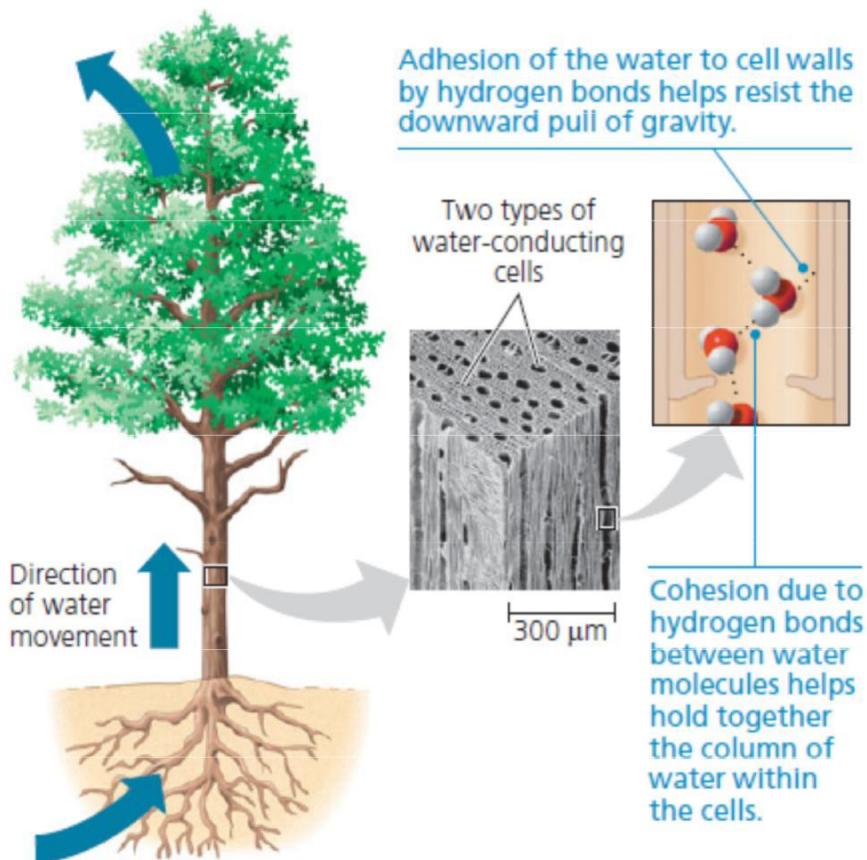


▲ **Figure 3.2 Hydrogen bonds between water molecules.**

The charged regions in a water molecule are due to its polar covalent bonds. Oppositely charged regions of neighboring water molecules are attracted to each other, forming hydrogen bonds. Each molecule can hydrogen-bond to multiple partners, and these associations are constantly changing.

Cohesive and adhesive properties of water

Water molecules stay close to each other as a result of hydrogen bonding. Although the arrangement of molecules in a sample of liquid water is constantly changing, at any given moment many of the molecules are linked by multiple hydrogen bonds. These linkages make water more structured than most other liquids. Collectively, the hydrogen bonds hold the substance together, a phenomenon called cohesion.



▲ Figure 3.3 Water transport in plants. Evaporation from leaves pulls water upward from the roots through water-conducting cells. Because of the properties of cohesion and adhesion, the tallest trees can transport water more than 100 m upward—approximately one-quarter the height of the Empire State Building in New York City.

Adhesion, the clinging of one substance to another, also plays a role. Adhesion of water to cell walls by hydrogen bonds helps counter the downward pull of gravity

Moderation of Temperature by Water

Water moderates air temperature by absorbing heat from air that is warmer and releasing the stored heat to air that is cooler. Water is effective as a heat bank because it can absorb or release a relatively large amount of heat with only a slight change in its own temperature. How it can do that?

The ability of water to stabilize temperature stems from its relatively high specific heat. The specific heat of water is 1 calorie per gram and per degree Celsius, abbreviated as 1 cal/g °C. Compared with most other substances, water has an unusually high specific heat. Because of the high specific heat of water relative to other materials, water will change its temperature less when

it absorbs or loses a given amount of heat. We can trace water's high specific heat, like many of its other properties, to hydrogen bonding. Heat must be absorbed in order to break hydrogen bonds; by the same token, heat is released when hydrogen bonds form. A calorie of heat causes a relatively small change in the temperature of water because much of the heat is used to disrupt hydrogen bonds before the water molecules can begin moving faster. And when the temperature of water drops slightly, many additional hydrogen bonds form, releasing a considerable amount of energy in the form of heat.

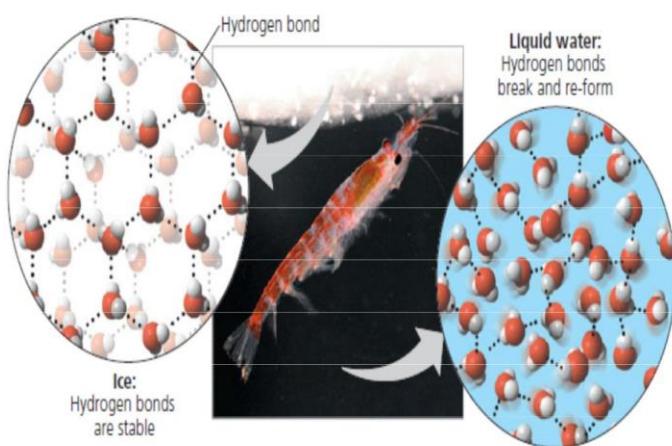
What is the relevance of water's high specific heat to life on Earth? A large body of water can absorb and store a huge amount of heat from the sun in the daytime and during summer while warming up only a few degrees. At night and during winter, the gradually cooling water can warm the air. This is the reason coastal areas generally have milder climates than inland regions. The high specific heat of water also tends to stabilize ocean temperatures, creating a favorable environment for marine life. Thus, because of its high specific heat, the water that covers most of Earth keeps temperature fluctuations on land and in water within limits that permit life.

Floating of Ice on Liquid Water

Water is one of the few substances that are less dense as a solid than as a liquid. In other words, ice floats on liquid water. While other materials contract and become denser when they solidify, water expands. How it helps for life?

► **Figure 3.6** Ice: crystalline structure and floating barrier. In ice, each molecule is hydrogen-bonded to four neighbors in a three-dimensional crystal. Because the crystal is spacious, ice has fewer molecules than an equal volume of liquid water. In other words, ice is less dense than liquid water. Floating ice becomes a barrier that protects the liquid water below from the colder air. The marine organism shown here is a type of shrimp called krill; it was photographed beneath floating ice in the Southern Ocean near Antarctica.

WHAT IF? If water did not form hydrogen bonds, what would happen to the shrimp's environment?

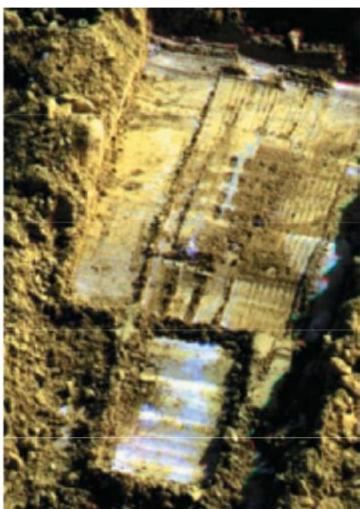


Water: The Solvent of Life

Water is a very good solvent. Many reactions take place in an organism. For almost all the reactions, water acts as a solvent.

Possible Evolution of Life on Other Planets with Water

Biologists who look for life elsewhere in the universe have concentrated their search on planets that might have water. To date, more than 200 planets have been found outside our solar system, and there is evidence for the presence of water vapor on one or two of them. In our own solar system, Mars has been most compelling to biologists as a focus of study. Like Earth, Mars has an ice cap at both poles.



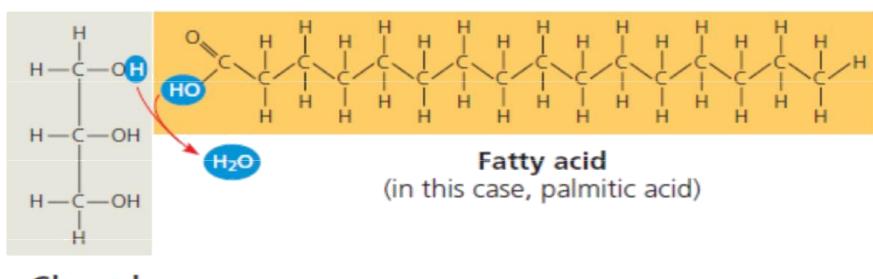
◀ **Figure 3.9 Subsurface ice and morning frost on Mars.** This photograph was taken by the Mars lander *Phoenix* in 2008. The trench was scraped by a robotic arm, uncovering ice (white in rectangle near bottom) below the surface material. Frost also appears as a white coating in several places in the upper half of the image. This photograph was colorized by NASA to highlight the ice.

Lipids and phospholipids:

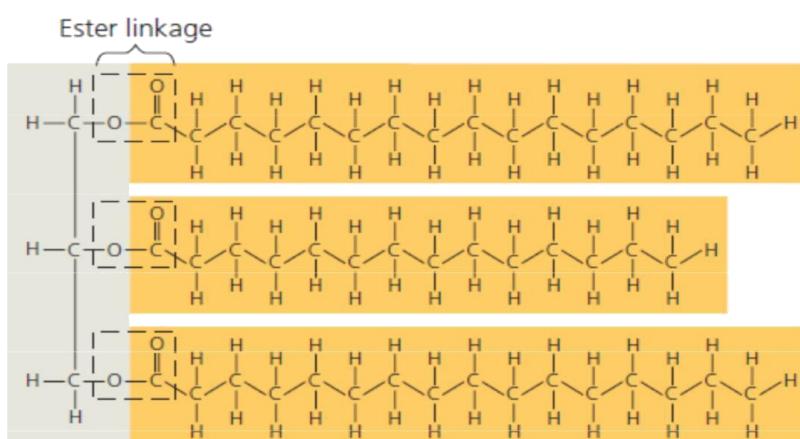
Lipids are hydrophobic molecules. The hydrophobic behavior of lipids is based on their molecular structure. Although they may have some polar bonds associated with oxygen, lipids consist mostly of hydrocarbon regions. Lipids are varied in form and function. They include waxes and certain pigments, but we will focus on the most biologically important types of lipids: fats & phospholipids.

A fatty acid has a long carbon skeleton, usually 16 or 18 carbon atoms in length. The carbon at one end of the skeleton is part of a carboxyl group, the functional group that gives these

molecules the name fatty acid. The rest of the skeleton consists of a hydrocarbon chain. The relatively nonpolar C–H bonds in the hydrocarbon chains of fatty acids are the reason fats are hydrophobic. Fats separate from water because the water molecules hydrogen bond to one another and exclude the fats. In making a fat, three fatty acid molecules are each joined to glycerol by an ester linkage, a bond between a hydroxyl group and a carboxyl group. The resulting fat, also called a triacylglycerol, thus consists of three fatty acids linked to one glycerol molecule.



(a) One of three dehydration reactions in the synthesis of a fat



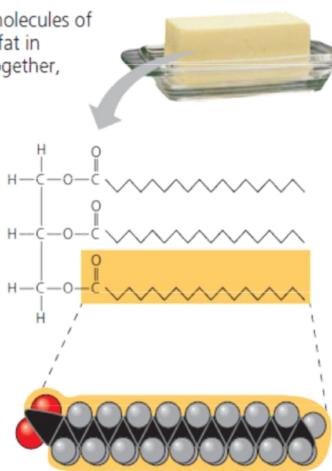
(b) Fat molecule (triacylglycerol)

The terms saturated fats and unsaturated fats are commonly used in the context of nutrition. These terms refer to the structure of the hydrocarbon chains of the fatty acids. If there are no double bonds between carbon atoms composing a chain, then as many hydrogen atoms as possible are bonded to the carbon skeleton. Such a structure is said to be saturated with hydrogen, and the resulting fatty acid therefore called a saturated fatty acid. An unsaturated fatty acid has one or more double bonds, with one fewer hydrogen atom on each double-bonded carbon. Nearly all double bonds in naturally occurring fatty acids are cis double bonds, which cause a kink in the hydrocarbon chain wherever they occur

(a) Saturated fat

At room temperature, the molecules of a saturated fat, such as the fat in butter, are packed closely together, forming a solid.

Structural formula of a saturated fat molecule (Each hydrocarbon chain is represented as a zigzag line, where each bend represents a carbon atom and hydrogens are not shown.)

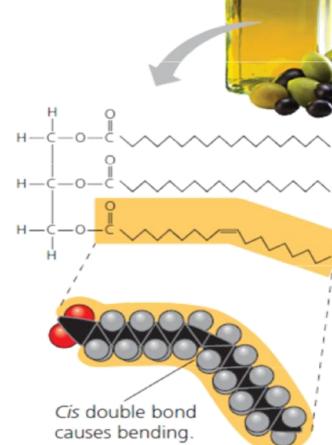


Space-filling model of stearic acid, a saturated fatty acid (red = oxygen, black = carbon, gray = hydrogen)

(b) Unsaturated fat

At room temperature, the molecules of an unsaturated fat such as olive oil cannot pack together closely enough to solidify because of the kinks in some of their fatty acid hydrocarbon chains.

Structural formula of an unsaturated fat molecule

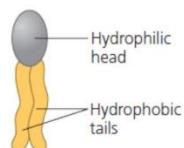
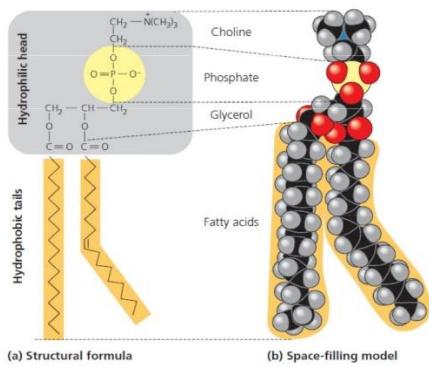


Space-filling model of oleic acid, an unsaturated fatty acid

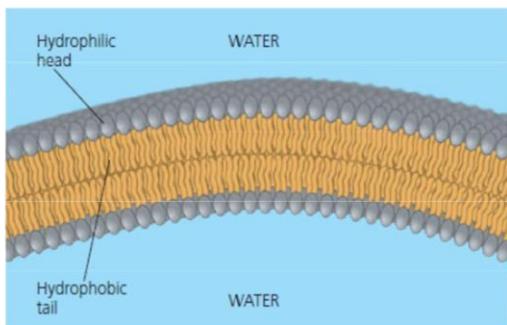
Cis double bond causes bending.

Phospholipids are essential for cells because they make up cell membranes. Phospholipid is similar to a fat molecule but has only two fatty acids attached to glycerol rather than three. The third hydroxyl group of glycerol is joined to a phosphate group, which has a negative electrical charge in the cell. Additional small molecules, which are usually charged or polar, can be linked to the phosphate group to form a variety of phospholipids. The two ends of phospholipids show different behaviour toward water. The hydrocarbon tails are hydrophobic and are excluded from water. However, the phosphate group and its attachments form a hydrophilic head that has an affinity for water. These strange behaviour molecules are called amphipathic molecules. When phospholipids are added to water, they self-assemble into double-layered structures called "bilayers," shielding their hydrophobic portions from water. At the surface of a cell, phospholipids are arranged in a similar bilayer. The hydrophilic heads of the molecules are on the outside of the

bilayer, in contact with the aqueous solutions inside and outside of the cell. The hydrophobic tails point toward the interior of the bilayer, away from the water. The phospholipid bilayer forms a boundary between the cell and its external environment; in fact, cells could not exist without phospholipids



(c) Phospholipid symbol

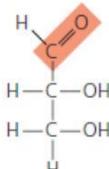
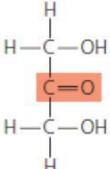
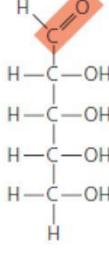
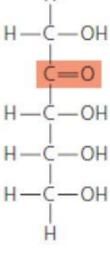
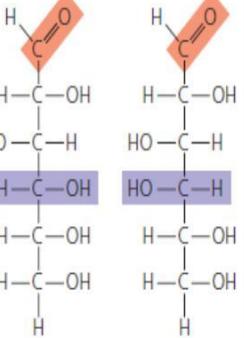
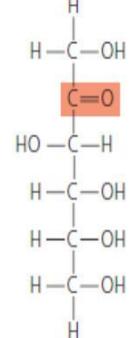


▲ Figure 5.13 Bilayer structure formed by self-assembly of phospholipids in an aqueous environment. The phospholipid bilayer shown here is the main fabric of biological membranes. Note that the hydrophilic heads of the phospholipids are in contact with water in this structure, whereas the hydrophobic tails are in contact with each other and remote from water.

Carbohydrates & ATP

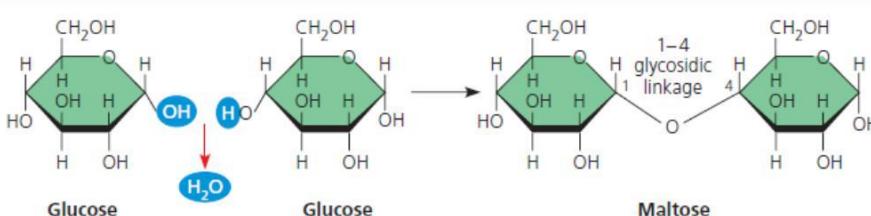
Carbohydrates include both sugars and polymers of sugars. The simplest carbohydrates are the monosaccharides, or simple sugars; these are the monomers from which more complex carbohydrates are constructed. Disaccharides are double sugars, consisting of two monosaccharides joined by a covalent bond. Carbohydrates also include macromolecules called polysaccharides, polymers composed of many sugar building blocks.

Monosaccharides (from the Greek monos, single, and sacchar, sugar) generally have molecular formulas that are some multiple of the unit CH_2O . Glucose ($\text{C}_6\text{H}_{12}\text{O}_6$) (multiple of six), the most common monosaccharide, is of central importance in the chemistry of life. In the structure of glucose, we can see the trademarks of a sugar: The molecule has a carbonyl group ($\text{C}=\text{O}$) and multiple hydroxyl groups ($-\text{OH}$). Depending on the location of the carbonyl group, a sugar is either an aldose (aldehyde sugar) or a ketose (ketone sugar). Glucose, for example, is an aldose; fructose, an isomer of glucose, is a ketose. (Most names for sugars end in -ose.) Another criterion for classifying sugars is the size of the carbon skeleton, which ranges from three to seven carbons long. Glucose, fructose, and other sugars that have six carbons are called hexoses. Trioses (three-carbon sugars) and pentoses (five-carbon sugars) are also common.

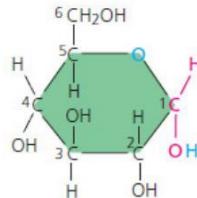
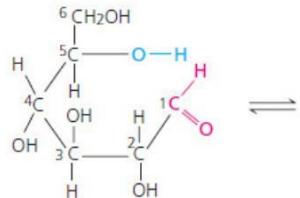
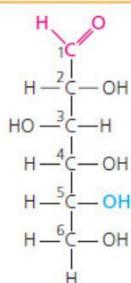
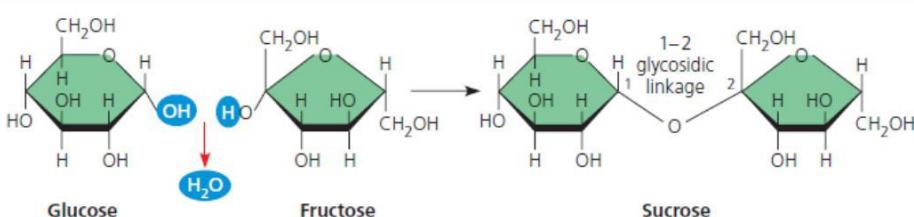
Aldoses (Aldehyde Sugars) Carbonyl group at end of carbon skeleton	Ketoses (Ketone Sugars) Carbonyl group within carbon skeleton
Trioses: 3-carbon sugars ($\text{C}_3\text{H}_6\text{O}_3$)	
 <p>Glyceraldehyde An initial breakdown product of glucose</p>	 <p>Dihydroxyacetone An initial breakdown product of glucose</p>
Pentoses: 5-carbon sugars ($\text{C}_5\text{H}_{10}\text{O}_5$)	
 <p>Ribose A component of RNA</p>	 <p>Ribulose An intermediate in photosynthesis</p>
Hexoses: 6-carbon sugars ($\text{C}_6\text{H}_{12}\text{O}_6$)	
 <p>Glucose Energy sources for organisms</p>	 <p>Galactose Energy sources for organisms</p>
	 <p>Fructose An energy source for organisms</p>

A disaccharide consists of two monosaccharides joined by a glycosidic linkage, a covalent bond formed between two monosaccharides by a dehydration reaction. For example, maltose is a disaccharide formed by the linking of two molecules of glucose. Also known as malt sugar, maltose is an ingredient used in brewing beer. The most prevalent disaccharide is sucrose, which is table sugar. Its two monomers are glucose and fructose. Plants generally transport carbohydrates from leaves to roots and other nonphotosynthetic organs in the form of sucrose. Lactose, the sugar present in milk, is another disaccharide, in this case a glucose molecule joined to a galactose molecule.

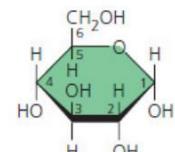
(a) Dehydration reaction in the synthesis of maltose. The bonding of two glucose units forms maltose. The glycosidic linkage joins the number 1 carbon of one glucose to the number 4 carbon of the second glucose. Joining the glucose monomers in a different way would result in a different disaccharide.



(b) Dehydration reaction in the synthesis of sucrose. Sucrose is a disaccharide formed from glucose and fructose. Notice that fructose, though a hexose like glucose, forms a five-sided ring.



(a) Linear and ring forms. Chemical equilibrium between the linear and ring structures greatly favors the formation of rings. The carbons of the sugar are numbered 1 to 6, as shown. To form the glucose ring, carbon 1 bonds to the oxygen attached to carbon 5.



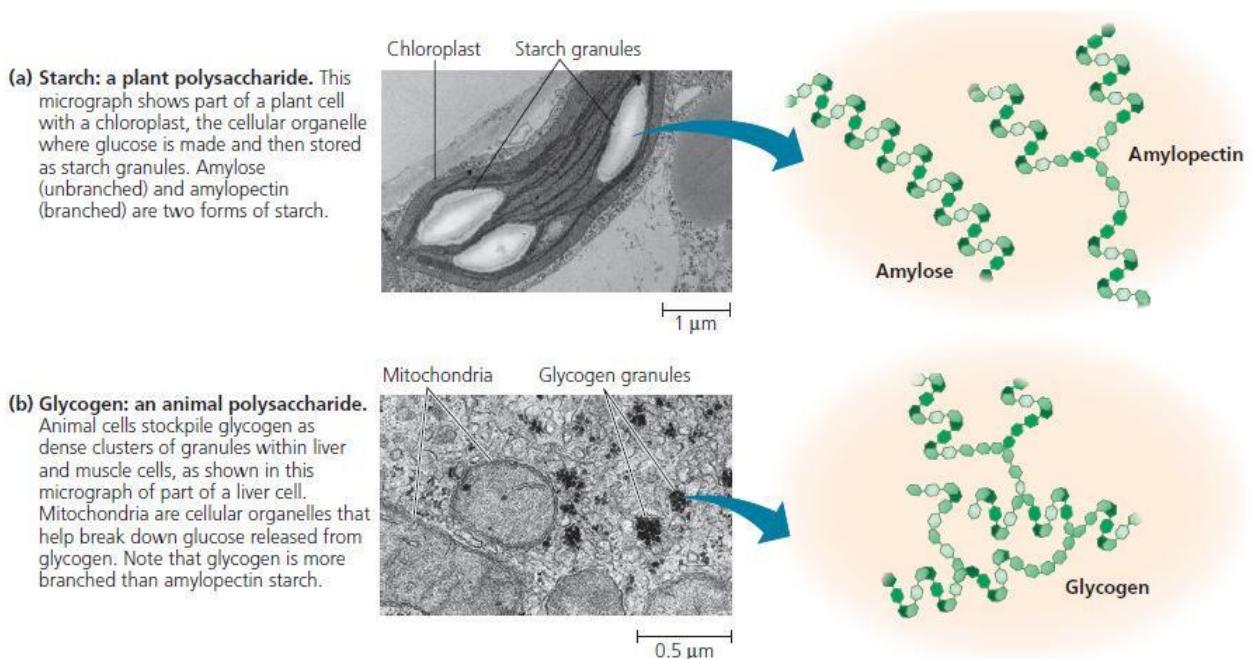
(b) Abbreviated ring structure. Each corner represents a carbon. The ring's thicker edge indicates that you are looking at the ring edge-on; the components attached to the ring lie above or below the plane of the ring.

Polysaccharides are macromolecules, polymers with a few hundred to a few thousand monosaccharides joined by glycosidic linkages. Some polysaccharides serve as storage material, hydrolyzed as needed to provide sugar for cells. Other polysaccharides serve as building material for structures that protect the cell or the whole organism. The architecture and function of a

polysaccharide are determined by its sugar monomers and by the positions of its glycosidic linkages.

Both plants and animals store sugars for later use in the form of storage polysaccharides. Plants store starch, a polymer of glucose monomers, as granules within cellular structures known as plastids, which include chloroplasts. Synthesizing starch enables the plant to stockpile surplus glucose. Because glucose is a major cellular fuel, starch represents stored energy. The sugar can later be withdrawn from this carbohydrate “bank” by hydrolysis, which breaks the bonds between the glucose monomers. Most animals, including humans, also have enzymes that can hydrolyze plant starch, making glucose available as a nutrient for cells. Potato tubers and grains—the fruits of wheat, maize (corn), rice, and other grasses—are the major sources of starch in the human diet.

Most of the glucose monomers in starch are joined by 1–4 linkages (number 1 carbon to number 4 carbon), like the glucose units in maltose. The simplest form of starch, amylose, is unbranched. Amylopectin, a more complex starch, is a branched polymer with 1–6 linkages at the branch points. Animals store a polysaccharide called glycogen, a polymer of glucose that is like amylopectin but more extensively branched. Humans and other vertebrates store glycogen mainly in liver and muscle cells. Hydrolysis of glycogen in these cells releases glucose when the demand for sugar increases.



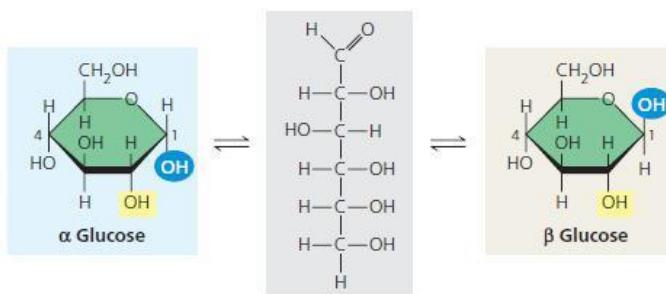
Structural Polysaccharides

Organisms build strong materials from structural polysaccharides. For example, the polysaccharide called cellulose is a major component of the tough walls that enclose plant cells. On a global scale, plants produce almost 10^{14} kg (100 billion tons) of cellulose per year; it is the most abundant organic compound on Earth. Like starch, cellulose is a polymer of glucose, but the glycosidic linkages in these two polymers differ. The difference is based on the fact that there are actually two slightly different ring structures for glucose. When glucose forms a ring, the hydroxyl group attached to the number 1 carbon is positioned either below or above the plane of the ring. These two ring forms for glucose are called alpha (α) and beta (β), respectively. In starch, all the glucose monomers are in the α configuration. The glucose monomers of cellulose are all in the β configuration, making every glucose monomer “upside down” with respect to its neighbors.

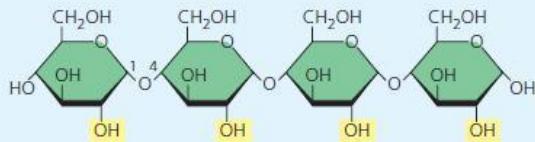
The differing glycosidic linkages in starch and cellulose give the two molecules distinct three-dimensional shapes. Whereas certain starch molecules are largely helical, a cellulose molecule is straight. Cellulose is never branched, and some hydroxyl groups on its glucose monomers are free to hydrogen-bond with the hydroxyls of other cellulose molecules lying parallel to it. In plant cell walls, parallel cellulose molecules held together in this way are grouped into units called microfibrils. These cable-like microfibrils are a strong building material for plants and an important substance for humans because cellulose is the major constituent of paper and the only component of cotton.

Enzymes that digest starch by hydrolyzing its α linkages are unable to hydrolyze the β linkages of cellulose because of the distinctly different shapes of these two molecules. In fact, few organisms possess enzymes that can digest cellulose. Animals, including humans, do not; the cellulose in our food passes through the digestive tract and is eliminated with the feces. Along the way, the cellulose abrades the wall of the digestive tract and stimulates the lining to secrete mucus, which aids in the smooth passage of food through the tract. Thus, although cellulose is not a nutrient for humans, it is an important part of a healthful diet. Most fresh fruits, vegetables, and whole grains are rich in cellulose. On food packages, “insoluble fiber” refers mainly to cellulose.

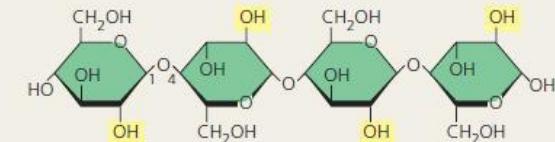
(a) α and β glucose ring structures. These two interconvertible forms of glucose differ in the placement of the hydroxyl group (highlighted in blue) attached to the number 1 carbon.



(b) Starch: 1–4 linkage of α glucose monomers. All monomers are in the same orientation. Compare the positions of the —OH groups highlighted in yellow with those in cellulose (c).



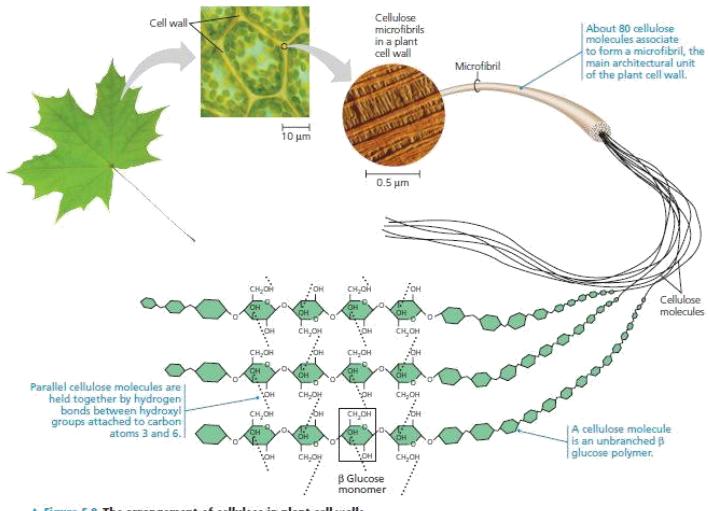
(c) Cellulose: 1–4 linkage of β glucose monomers. In cellulose, every β glucose monomer is upside down with respect to its neighbors.



Some microorganisms can digest cellulose, breaking it down into glucose monomers. A cow harbors cellulose digesting prokaryotes and protists in its stomach. These microbes hydrolyze the cellulose of hay and grass and convert the glucose to other compounds that nourish the cow. Similarly, a termite, which is unable to digest cellulose by itself, has prokaryotes or protists living in its gut that can make a meal of wood.

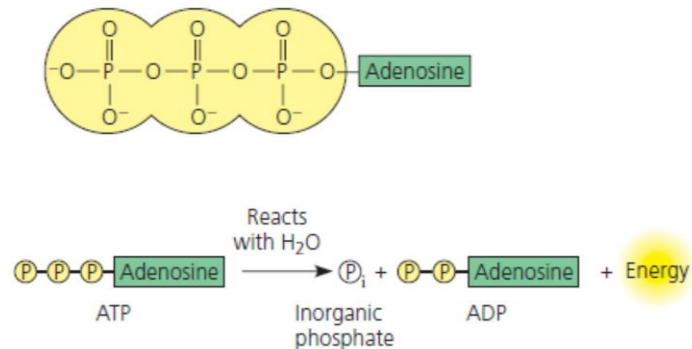
Adenosine triphosphate (ATP)

ATP is an important source of energy for cellular processes. ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups: Where three phosphates are present in series, as in ATP, one phosphate may be split off as a result of a reaction with water. This inorganic phosphate ion, HOPO_3^{2-} , is often referred as a phosphate group.



▲ Figure 5.8 The arrangement of cellulose in plant cell walls.

While losing this group, it releases energy equivalent to 7.3 Kcal/mol. Energy required for most of the chemical reactions in the cell is used by releasing phosphate group. Energy is also stored in the form of ATP by the cell.

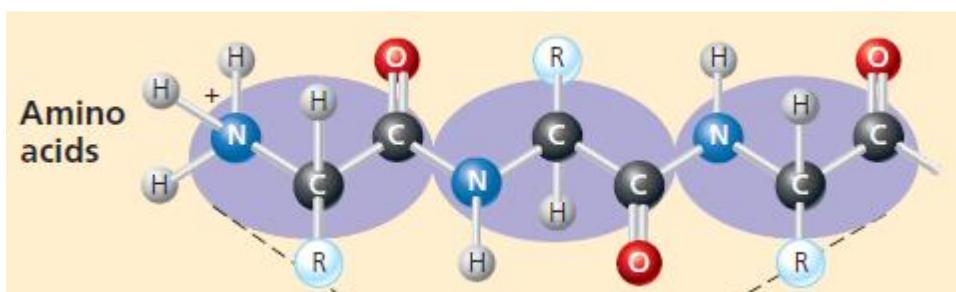


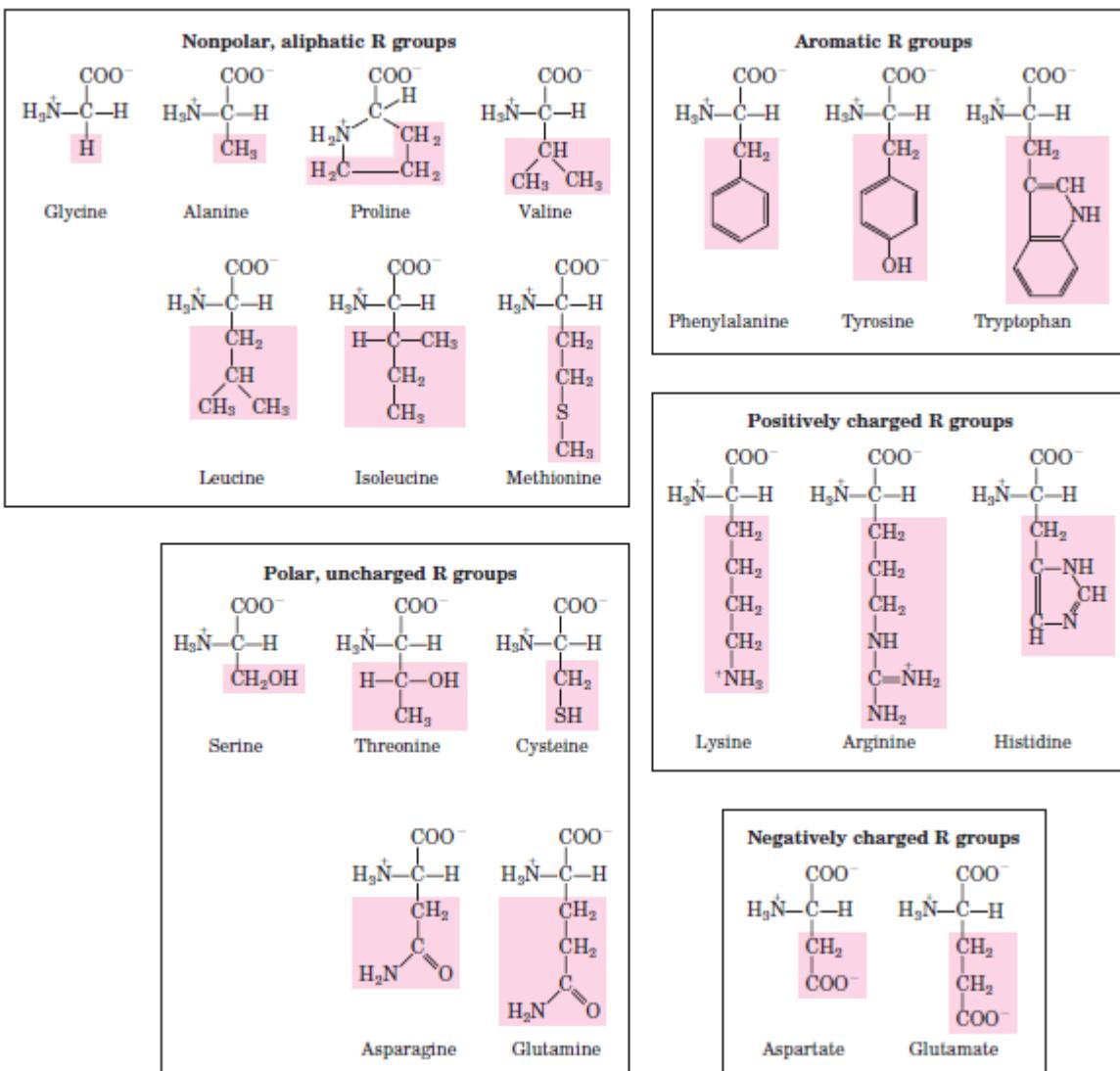
Proteins and their structure

Proteins are the most abundant biological macromolecules, occurring in all parts of the cell. Proteins also occur in great variety; thousands of different kinds, ranging in size from relatively small peptides to huge polymers with molecular weights in millions. Nearly every dynamic function of a living being depends on proteins. In fact, the importance of proteins is underscored by their name, which comes from the Greek word *proteios*, meaning "first," or "primary." Proteins account for more than 50% of the dry mass of most cells, and they are instrumental in almost everything the organism does. Some proteins speed up chemical reactions, while others play a role in defense, storage, transport, cellular communication, movement, or structural support.

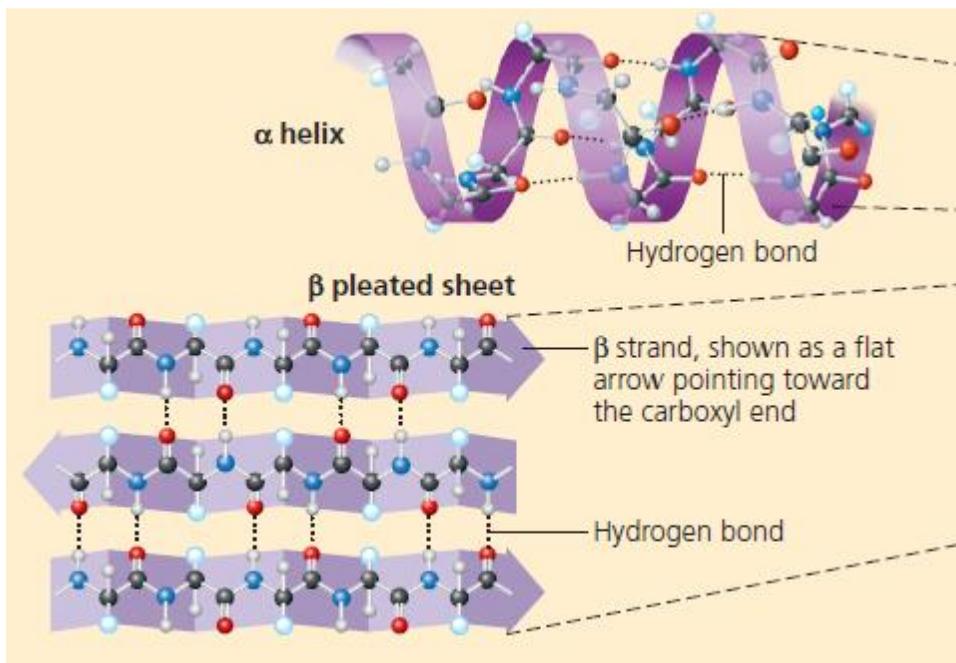
The basic building blocks of proteins are amino acids. Twenty different amino acids are commonly found in proteins. All 20 of the common amino acids are α -amino acids. They have a carboxyl group and an amino group bonded to the same carbon atom (α carbon). They differ from each other in their side chains, or **R groups**, which vary in structure, size, and electric charge, and which influence the solubility of the amino acids in water. The common amino acids of proteins have been assigned three-letter abbreviations and one-letter symbols, which are used as shorthand to indicate the composition and sequence of amino acids polymerized in proteins.

The **primary structure** of a protein is simply the linear arrangement, or *sequence*, of the amino acid residues that compose it. Many terms are used to denote the chains formed by the polymerization of amino acids. A short chain of amino acids linked by peptide bonds and having a defined sequence is called a **peptide**; longer chains are referred to as **polypeptides**. Peptides generally contain less than 20–30 amino acid residues, whereas polypeptides contain as many as 4000 residues. We generally reserve the term **protein** for a polypeptide (or for a complex of polypeptides) that has a well-defined three-dimensional structure.



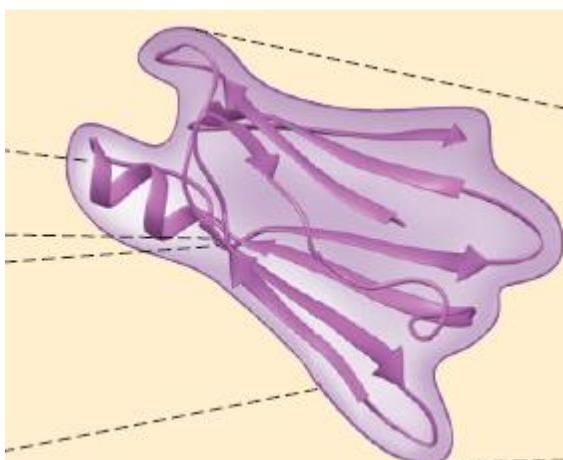
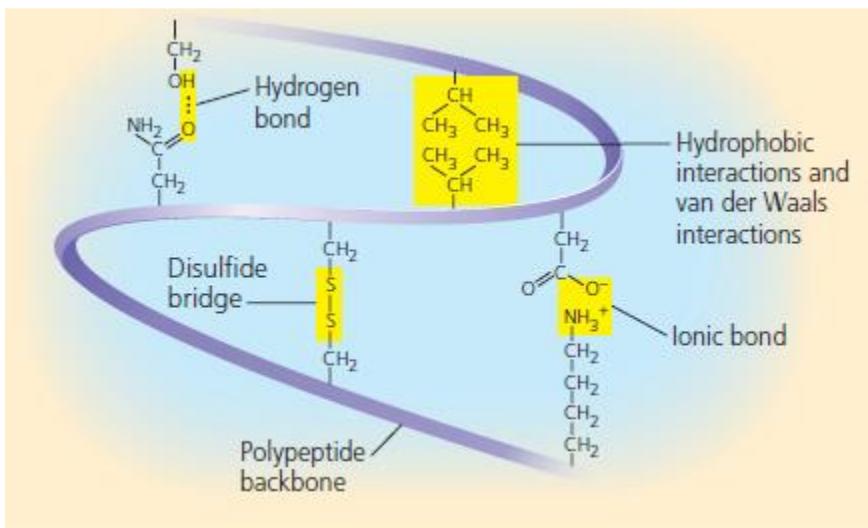


Secondary structure, are the result of hydrogen bonds between the repeating constituents of the polypeptide backbone (not the amino acid side chains). Within the backbone, the oxygen atoms have a partial negative charge, and the hydrogen atoms attached to the nitrogen have a partial positive charge; therefore, hydrogen bonds can form between these atoms. Individually, these hydrogen bonds are weak, but because they are repeated many times over a relatively long region of the polypeptide chain, they can support a particular shape for that part of the protein. One such secondary structure is the **α -helix**, a delicate coil held together by hydrogen bonding between every fourth amino acid. The other main type of secondary structure is the **β -pleated sheet**. In this structure two or more strands of the polypeptide chain lying side by side (called β strands) are connected by hydrogen bonds between parts of the two parallel polypeptide backbones.



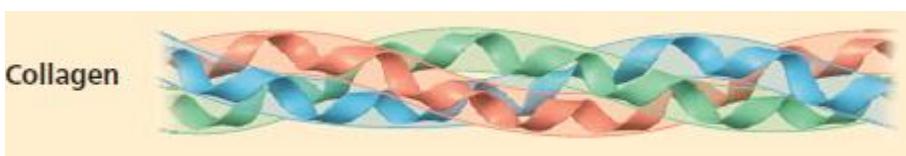
Turns Composed of three or four residues, turns are located on the surface of a protein, forming sharp bends that redirect the polypeptide backbone back toward the interior. These short, U-shaped secondary structures are stabilized by a hydrogen bond between their end residues. Glycine and proline are commonly present in turns. The lack of a large side chain in glycine and the presence of a built-in bend in proline allow the polypeptide backbone to fold into a tight U shape. Turns allow large proteins to fold into highly compact structures. A polypeptide backbone also may contain longer bends, or *loops*. In contrast with turns, which exhibit just a few well-defined structures, loops can be formed in many different ways.

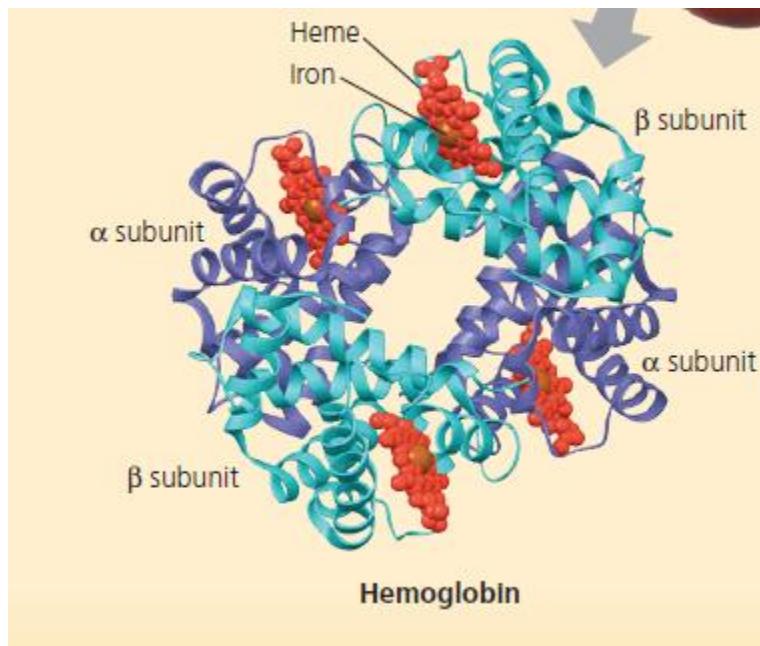
Tertiary structure is the overall shape of a polypeptide resulting from interactions between the side chains (R groups) of various amino acids. One type of interaction that contributes to tertiary structure is—somewhat misleadingly—called a **hydrophobic interaction**. As a polypeptide folds into its functional shape, amino acids with hydrophobic (nonpolar) side chains usually end up in clusters at the core of the protein, out of contact with water. Thus, a “hydrophobic interaction” is actually caused by the exclusion of nonpolar substances by water molecules. Once nonpolar amino acid side chains are close together, van der Waals interactions help hold them together. Meanwhile, hydrogen bonds between polar side chains and ionic bonds between positively and negatively charged side chains also help stabilize tertiary structure. These are all weak interactions in the aqueous cellular environment, but their cumulative effect helps give the protein a unique shape. Covalent bonds called **disulfide bridges** may further reinforce the shape of a protein. Disulfide bridges form where two cysteine monomers, which have sulphydryl groups ($-SH$) on their side chains, are brought close together by the folding of the protein. The sulfur of one cysteine bonds to the sulfur of the second, and the disulfide bridge ($-S-S-$) rivets parts of the protein together. All of these different kinds of interactions can contribute to the tertiary structure of a protein.



Tertiary Structure of a Protein.

Quaternary structure is the overall protein structure that results from the aggregation of these polypeptide subunits. Example: collagen, which is a fibrous protein that has three identical helical polypeptides intertwined into a larger triple helix, giving the long fibers great strength. This suits collagen fibers to their function as the girders of connective tissue in skin, bone, tendons, ligaments, and other body parts. Collagen accounts for 40% of the protein in a human body. Hemoglobin, the oxygen-binding protein of red blood cells is another example of a globular protein with quaternary structure. It consists of four polypeptide subunits, two of one kind (α) and two of another kind (β). Both α and β subunits consist primarily of α -helical secondary structure. Each subunit has a nonpolypeptide component, called heme, with an iron atom that binds oxygen.





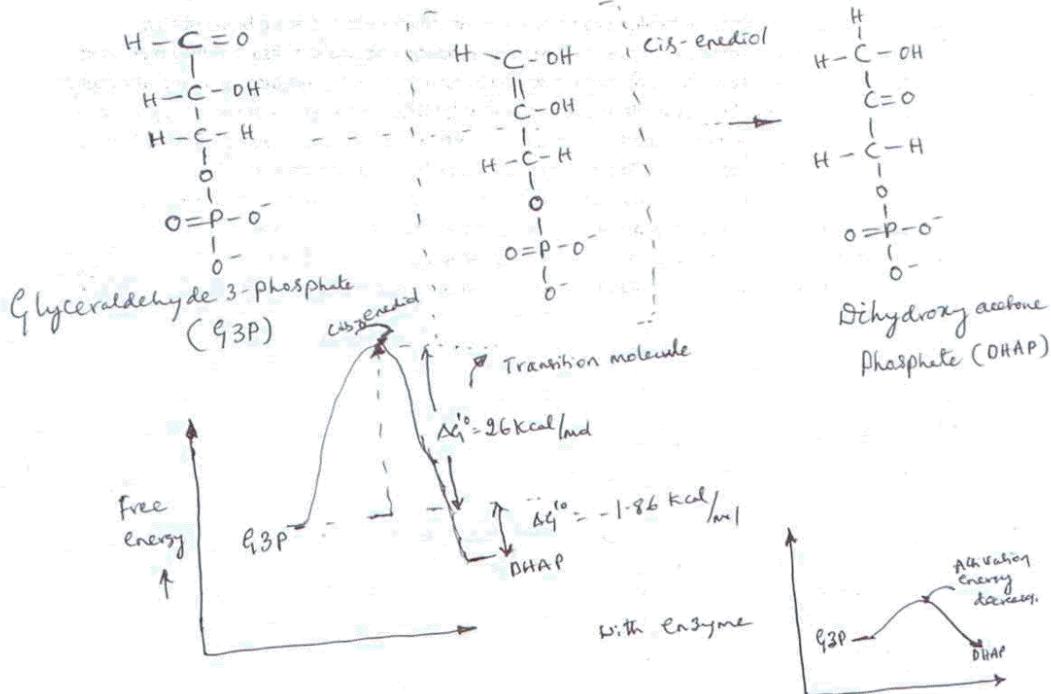
Enzymes and how enzymes functions

Enzymes

Enzymes are the most remarkable and highly specialized proteins. Enzymes have extraordinary catalytic power, often far greater than that of synthetic or inorganic catalysts. They have a high degree of specificity for their substrates, they accelerate chemical reactions tremendously, and they function in aqueous solutions under very mild conditions of temperature and pH. Like all catalysts, enzymes do not affect the extent of a reaction, which is determined by the change in free energy ΔG° between reactants and products. For reactions that are energetically favorable, enzymes increase the reaction rate by lowering the activation energy.

Edward Buchner (Nobel prize in chemistry-1907) initially showed that fermentation can be done with yeast juice rather than yeast itself. The word enzyme came from the latin word 'Zyma' means yeast and 'enzyme' means something in yeast.

To understand more about enzymes, we will take an example of an enzyme which is present in almost all organisms, called triose phosphate isomerase. The enzyme converts one triose sugar with phosphate group (glyceraldehyde 3-phosphate (G3P)) to another form of triose sugar with phosphate group (Dihydroxy acetone phosphate (DHAP)) which is energetically favourable reaction ($\Delta G^\circ = -1.86$ Kcal/mol). While converting from G3P to DHAP, it has to go through a molecule called cis-enediol (transition molecule). It is energetically unfavourable molecule ($\Delta G^\circ = + 26$ Kcal/mol). It is so unstable, once cis-enediol forms, the phosphate group comes out of molecule especially in presence of water. Though formation of DHAP from G3P is energetically favourable, since it has to go through a transition molecule, which is energetically unfavourable, the formation of product in normal condition is impossible. Enzyme helps to stabilize this transition state and helps in formation of product.

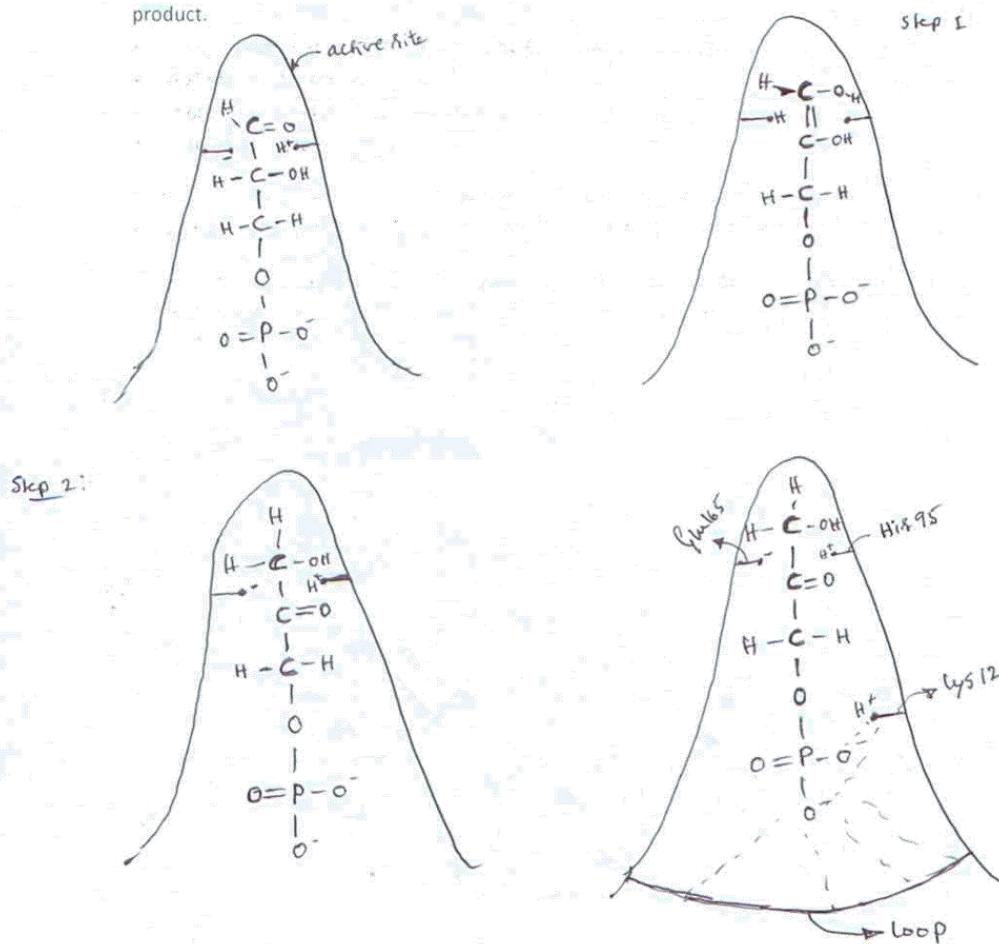


Important points about enzymes:

- It does not change energetic favourability
- It does change activation barrier (reduces activation barrier)
- It stabilizes the transition state
- It prevents side reaction to occur
- It speeds up the reaction

Triose phosphate isomerase is a perfect enzyme! The rate limiting step is the rate at which molecules diffuse into it. Once the substrate is in its active site, the product will be formed.

How does triose phosphate isomerase works? It is 250 amino acid polypeptide chain and it is present in the form of dimer. Few amino acids in the active site helps to convert substrate to product.



His95, i.e. the 95th aminoacid is histidine. It is positively charged aminoacid. It is exactly present at the position to give H⁺ ion to first carbon of G3P. Glutamic acid is present at 165th position. The negatively charged ion is appropriately present to take H⁺ from the second carbon of G3P. The resulting molecule is cis-enediol. It is highly unstable molecule.

In the second step, H⁺ ion from the second carbon is taken by His95 to become again positive charge and H⁺ ion from the glutamic acid to the first carbon atom of the molecule. The resulting molecule is DHAP.

To stabilize the phosphate group (which is negatively charged), lysine is present at the 12th aminoacid. The positively charged lysine electrostatically interacts with the phosphate group and helps in stabilizing it.

When this is in the cis-enediol state, the phosphate will normally come off pretty spontaneously & quickly. It will lose the phosphate and turn into what's called methylglyoxal. Actually it turns out that it's even going to float away in water if it's not sufficiently well bound.

A loop part of the protein closes down on the active site. And four polar amino acids make hydrogen bonds with the molecule & it prevents this intermediate from floating away. Because it's closed down, it actually prevents water getting into active site and so it protects it.

Let us analyze active site with different amino acids and whether the enzyme can able to convert G3P to DHAP?

If we make triosephosphate isomerase and substituted, instead of at position 165 a glutamic acid, an aspartic acid, would it work? Turns out it'll work 1,000 times worse. It will just work, it's about 1,000-fold worse in speed. Check the difference in structure of Glu & Asp, little one extra carbon bond positioning in the right place makes a difference of 1,000-fold to the speed of the enzyme.

Suppose we change lysine at 12th position to a non-charged amino acid. Let's change it to Leucine, a hydrophobic amino acid. Does the enzyme work? No. Turns out the enzyme doesn't even work. We can't get it to catalyze at all! But what if we change it to another positive amino acid? How about arginine? If we substitute an arginine instead of lysine, well, it still works, but it's about 200 times worse, because the positive charge is not in the ideal place.

Suppose if we remove the loop that closes the active site, and keep everything else in its position, does it work? It is about 100,000-times worse in speed. That loop really matters.

Bioenergetics

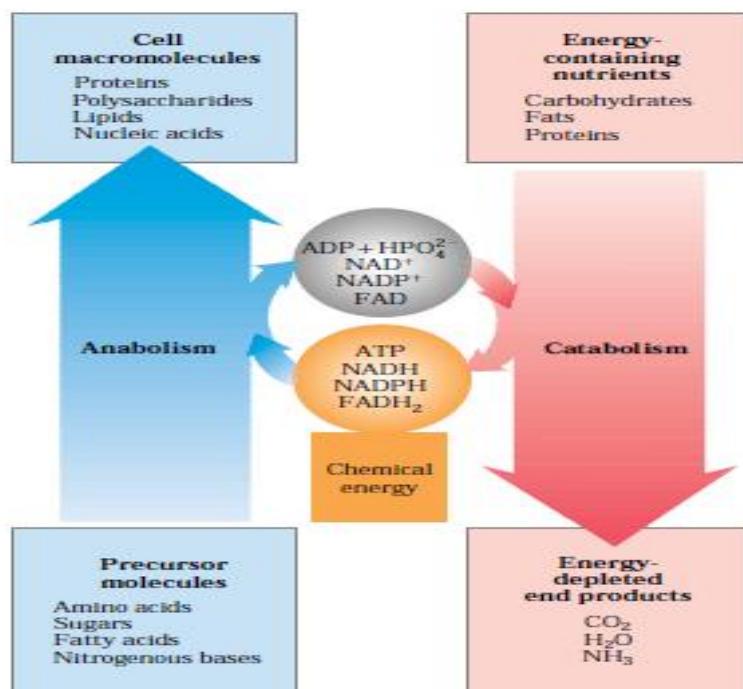
Biochemical Pathways

Living organisms can be divided into two large groups according to the chemical form in which they obtain carbon from the environment. **Autotrophs** can use carbon dioxide from the atmosphere as their sole source of carbon, from which they construct all their carbon containing biomolecules. **Heterotrophs** cannot use atmospheric carbon dioxide and must obtain carbon from their environment in the form of relatively complex organic molecules such as glucose. Multicellular animals and most microorganisms are heterotrophic.

Metabolism, the sum of all the chemical transformations taking place in a cell or organism, occurs through a series of enzyme-catalyzed reactions that constitute **metabolic pathways**. Each of the consecutive steps in a metabolic pathway brings about a specific, small chemical change, usually the removal, transfer, or addition of a particular atom or functional group. The precursor is converted into a product through a series of metabolic intermediates called metabolites. The term intermediary metabolism is often applied to the combined activities of all the metabolic pathways that interconvert precursors, metabolites, and products of low molecular weight.

Catabolism is the degradative phase of metabolism in which organic nutrient molecules (carbohydrates, fats, and proteins) are converted into smaller, simpler end products. Catabolic pathways release energy, some of which is conserved in the formation of ATP and reduced electron carriers (NADH, NADPH, and FADH₂); the rest is lost as heat.

In **anabolism**, also called biosynthesis, small, simple precursors are built up into larger and more complex molecules, including lipids, polysaccharides, proteins, and nucleic acids. Anabolic reactions require an input of energy, generally in the form of the phosphoryl group transfer potential of ATP and the reducing power of NADH, NADPH, and FADH₂.



For metabolism, catabolism and anabolism to occur in the cell, the substrate has to go through **biochemical pathways**. The goal of the lecture is to understand the energetics of typical pathway reactions and **the basic principles of energetics of any biochemical reaction**.

In all the heterotrophs glycolysis (breaking up of sugar) takes place. In this biochemical pathway glucose is converted in to pyruvate. To understand the energetics of typical pathways of reaction, glycolysis is studied as an example. Before that, we will understand the basics of chemical reaction energetics.

Energetics of the reaction: Because biological systems are generally held at constant temperature and pressure, it is possible to predict the direction of a chemical reaction from the change in the free energy G , named after J. W. Gibbs, who showed that “all systems change in such a way that free energy [G] is minimized.” In the case of a chemical reaction, reactants \leftrightarrow products, the change in free energy ΔG is given by

$$\Delta G_{\text{products}} - \Delta G_{\text{reactants}}$$

The relation of ΔG to the direction of any chemical reaction can be summarized in three statements:

- If ΔG is negative, the forward reaction (from left to right as written) will tend to occur spontaneously.
- If ΔG is positive, the reverse reaction (from right to left as written) will tend to occur.
- If ΔG is zero, both forward and reverse reactions occur at equal rates; the reaction is at equilibrium.

The standard free-energy change of a reaction ΔG° is the value of the change in free energy under the conditions of 298 K (25°C), 1 atm pressure, pH 7.0 (as in pure water), and initial concentrations of 1 M for all reactants and products except protons, which are kept at 10^{-7} M (pH 7.0). Most biological reactions differ from standard conditions, particularly in the concentrations of reactants, which are normally less than 1 M.

The actual change in free energy ΔG during a reaction is influenced by temperature, pressure, and the initial concentrations of reactants and products and usually differs from ΔG° . Most biological reactions—like others that take place in aqueous solutions—also are affected by the pH of the solution. We can estimate free-energy changes for different temperatures and initial concentrations, using the equation

$$\Delta G = \Delta G^\circ + RT \ln [Q] = \Delta G^\circ + RT \ln [\text{product}/\text{reactant}]$$

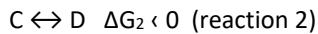
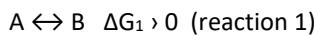
Where R is the gas constant of 1.987 cal/(degree·mol), T is the temperature (in degrees Kelvin), and Q is the initial concentration ratio of products to reactants.

Regardless of the ΔG° for a particular biochemical reaction, it will proceed spontaneously within cells only if ΔG is negative, given the usual intracellular concentrations of reactants and products. For example, the conversion of glyceraldehyde 3-phosphate (G3P) to dihydroxyacetone phosphate (DHAP), $\text{G3P} \leftrightarrow \text{DHAP}$ has a ΔG° of -1.840 kcal/mol. If the initial concentrations of G3P and DHAP are equal, then $\Delta G = G^\circ$, because $RT \ln 1 = 0$; in this situation, the reversible reaction $\text{G3P} \leftrightarrow \text{DHAP}$ will proceed in the direction of DHAP formation until equilibrium is reached. However, if the initial [DHAP] is 0.1 M and the initial [G3P] is 0.001 M, with other conditions being standard, then Q in Equation given equals $0.1/0.001 = 100$, giving a ΔG of + 0.887 kcal/mol. Under these conditions, the reaction will proceed in the direction of formation of G3P.

The ΔG for a reaction is independent of the reaction rate. Indeed, under usual physiological conditions, few, if any, of the biochemical reactions needed to sustain life would occur without some mechanism for increasing reaction rates. As we described in the previous lecture, the rates of reactions in biological systems are usually determined by the activity of **enzymes**, the protein catalysts that accelerate the formation of products from reactants without altering the value of ΔG .

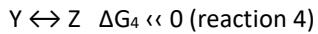
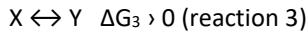
Cellular processes use two tricks in energetics to make energetically unfavorable reactions into favorable ones.

Trick 1) An Unfavorable Chemical Reaction Can Proceed If It Is directly coupled with an Energetically Favorable Reaction: Many processes in cells are energetically unfavorable ($\Delta G > 0$) and will not proceed spontaneously. Cells can carry out an energy-requiring reaction ($\Delta G_1 > 0$) by coupling it to an energy-releasing reaction ($\Delta G_2 < 0$) if the sum of the two reactions has a net negative ΔG . Suppose



In most of the directly coupled reactions, cellular processes use $ATP \leftrightarrow ADP + P_i \quad \Delta G = -7.3 \text{ kcal/mol}$ as reaction 2.

Trick 2) An Unfavorable Chemical Reaction Can Proceed If It Is indirectly coupled with an Energetically Favorable Reaction: Suppose



If the concentration of Y is zero and concentration of X increases, due to very high concentration difference (analyze with the equation $\Delta G = \Delta G^\circ + RT \ln [Q] = \Delta G^\circ + RT \ln [\text{product}/\text{reactant}]$) some amount of Y is going to form. Since the reaction $Y \leftrightarrow Z \quad \Delta G_2 << 0$, Y will be converted to Z spontaneously.

Now let us analyze the bioenergetics of glycolysis pathway. In glycolysis 6 carbon sugar glucose is converted into 3 carbon pyruvate. In anaerobic condition, in some organisms pyruvate will be converted to ethanol and carbon dioxide. In some organisms, it is converted into lactate. First one billion years after the existence of life, this was the only pathway used by cellular processes to produce energy. The step-by-step conversion of glucose to pyruvate is given in the figure (not necessary to remember). Analyze the pathway- wherever ΔG° becomes positive, direct or indirect coupling of reaction takes place in the pathway and cellular processes keep ΔG always negative or zero.



↓
Ethanol + CO₂
(yeast)

↓
Lactate
(human)

Glycolysis

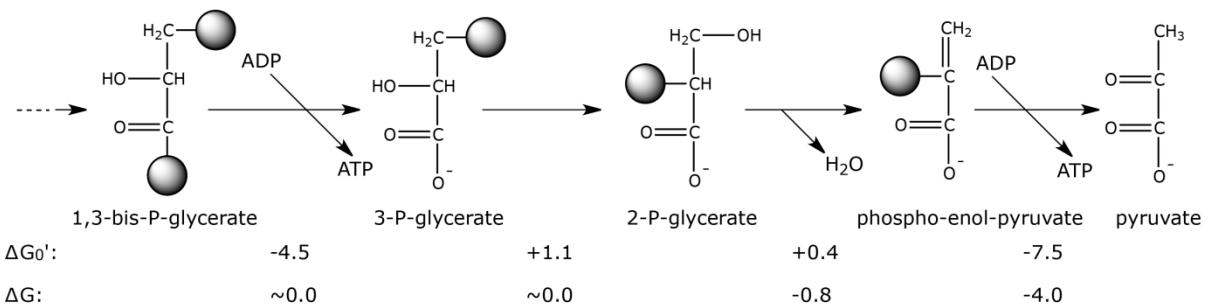
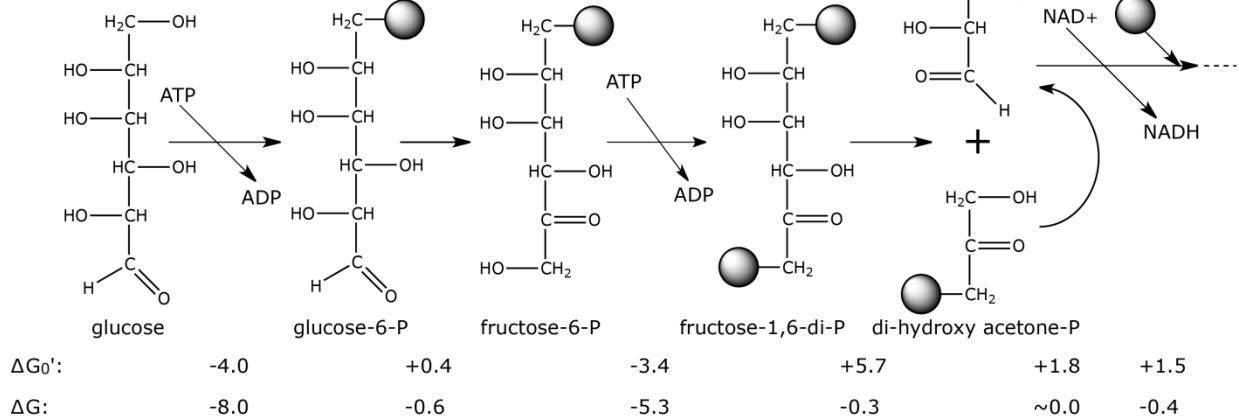
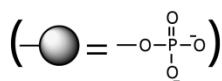
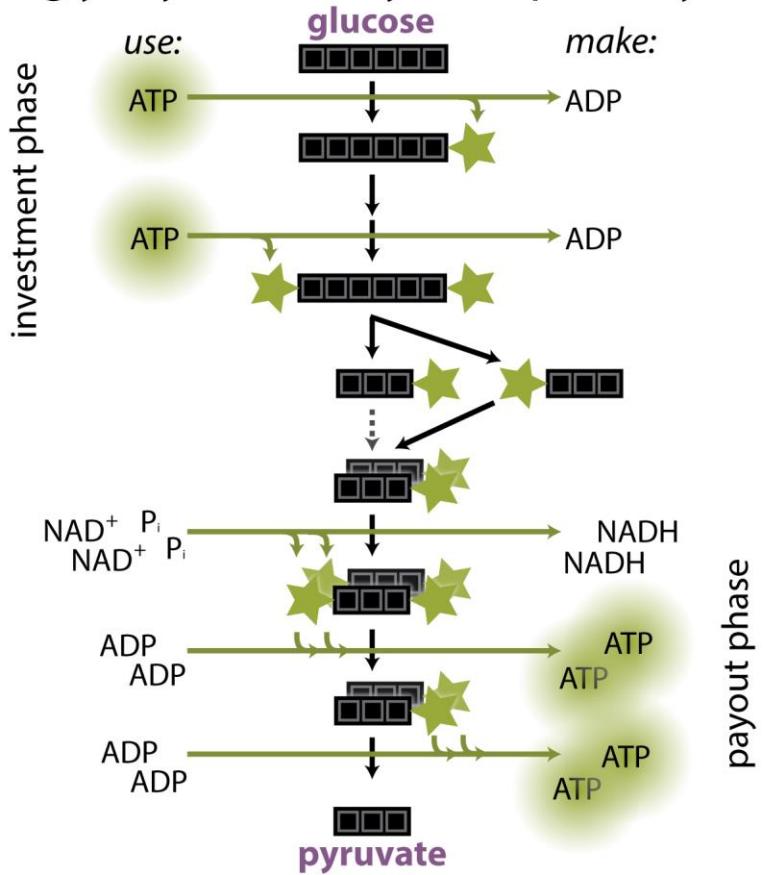
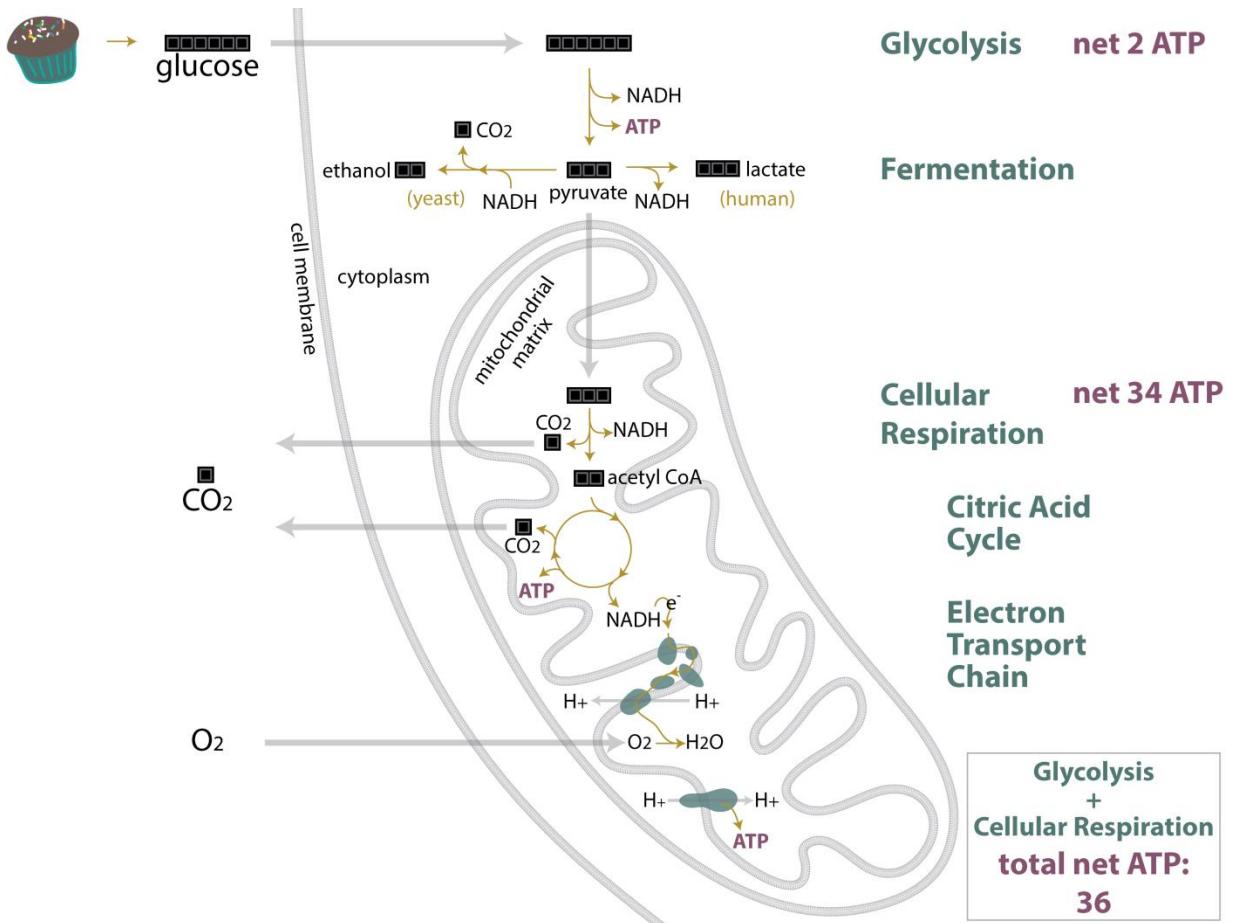


figure by Brian White

Calculate the amount of ATP produced by the glycolysis pathway. The net ATP produced is 4-2= 2. Two ATP's are invested to produce 4 ATPs.

glycolysis: an enzymatic pathway





After glycolysis pyruvate moves into mitochondria in aerobic organisms and produces 34 ATPs by utilizing oxygen as shown in the figure. The biochemical pathways of glycolysis, respiration, anabolic reactions are interrelated as shown in the picture below.

pH

When some substances dissolve in water, they release *hydrogen ions* (H⁺), which are actually single, positively charged protons. Hydrogen ions can attach to other molecules and change their properties. For example, the protons in “acid rain” can damage plants, and you probably have experienced the excess of hydrogen ions that we call “acid indigestion.” Here we will examine the properties of acids (defined as substances that release H⁺) and bases (defined as substances which accept H⁺). We will distinguish between strong and weak acids and bases and provide a quantitative means for stating the concentration of H⁺ in solutions: the **pH** scale.

ACIDS RELEASE H⁺ When hydrochloric acid (HCl) is added to water, it dissolves, releasing the ions H⁺ and Cl⁻:



Because its H⁺ concentration has increased, such a solution is *acidic*. Acids are substances that *release* H⁺ ions in solution. HCl is an acid, as is H₂SO₄ (sulfuric acid). One molecule of sulfuric acid will ionize to yield two H⁺ and one SO₄²⁻. Biological compounds that contain —COOH (the carboxyl group) are also acids because —COOH → —COO⁻ + H⁺. Acids that fully ionize in solution, such as HCl and H₂SO₄ are called *strong acids*. However, not all acids ionize fully in water. For example, if acetic acid (CH₃COOH) is added to water, some will dissociate into two ions (CH₃COO⁻ and H⁺), but some of the original acetic acid remains as well. Because the reaction is *not complete*, acetic acid is a *weak acid*.

BASES ACCEPT H⁺ Bases are substances that *accept* H⁺ in solution. Just as with acids, there are strong and weak bases. If NaOH (sodium hydroxide) is added to water, it dissolves and ionizes, releasing OH⁻ and Na⁺ ions:



Because the concentration of OH⁻ increases and OH⁻ absorbs H⁺ to form water (OH⁻ + H⁺ → H₂O), such a solution is *basic*. Because this reaction is complete, NaOH is a *strong base*. Weak bases include the bicarbonate ion (HCO₃⁻), which can accept a H⁺ ion and become carbonic acid (H₂CO₃), and ammonia (NH₃), which can accept a H⁺ and become an ammonium ion (NH₄⁺). Biological compounds that contain —NH₂ (the amino group) are also bases because



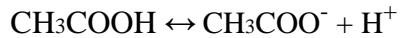
ACID–BASE REACTIONS MAY BE REVERSIBLE, when acetic acid is dissolved in water, two reactions happen. First, the acetic acid forms its ions:



Then, once the ions are formed, some of them re-form acetic acid:



This pair of reactions is reversible. A **reversible reaction** can proceed in either direction—left to right or right to left—depending on the relative starting concentrations of the reactants and products. The formula for a reversible reaction can be as



In terms of acids and bases, there are two types of reactions, depending on the extent of the reversibility:

- The ionization of strong acids and bases in water is virtually irreversible.
- The ionization of weak acids and bases in water is somewhat reversible.

WATER IS A WEAK ACID AND A WEAK BASE The water molecule has a slight but significant tendency to ionize into a hydroxide ion (OH^-) and a hydrogen ion (H^+). Actually, two water molecules participate in this reaction. One of the two molecules “captures” a hydrogen ion from the other, forming a hydroxide ion and a hydronium ion:



The hydronium ion is, in effect, a hydrogen ion bound to a water molecule. For simplicity, biochemists tend to use a modified representation of the ionization of water:



The ionization of water is important to all living creatures. This fact may seem surprising, since only about one water molecule in 500 million is ionized at any given time. But this is less surprising if we focus on the abundance of water in living systems, and the reactive nature of the H^+ ions produced by ionization.

- Pure water has a H^+ concentration of 10^{-7} M .
- A 1 M HCl solution has a H^+ concentration of 1 M .
- A 1 M NaOH solution has a H^+ concentration of 10^{-14} M .

This is a very wide range of numbers to work with—think about the decimals! It is easier to work with the *logarithm* of the H^+ concentration, because logarithms compress this range as shown in figure.

Since the H^+ concentration of pure water is 10^{-7} M , its pH is $-\log(10^{-7}) = -(-7)$, or 7. A smaller negative logarithm means a larger number. In practical terms, a lower pH means a higher H^+ concentration, or greater acidity. In 1 M HCl , the H^+ concentration is 1 M , so the pH is the negative logarithm of 1 ($-\log 10^0$), or 0. The pH of 1 M NaOH is the negative logarithm of 10^{-14} , or 14. A solution with a pH of less than 7 is acidic—it contains more H^+ ions than OH^- ions. A solution with a pH of 7 is *neutral* (without net charge), and a solution with a pH value greater than 7 is basic.

Why is this discussion of pH so important in biology? Many biologically important molecules contain charged groups (e.g., $-\text{COO}^-$) that can interact with the polar regions of water to form their structures. But these groups can combine with H^+ or other ions in their environment to form uncharged groups (e.g., $-\text{COOH}$). These uncharged groups have much less tendency to

interact with water. If such a group is part of a larger molecule, it might now induce the molecule to fold in such a way that it stays away from water because it is hydrophobic. In a more acidic environment, a negatively charged group such as —COO^- is more likely to combine with H^+ . So the pH of a biological tissue is a key to the three-dimensional structures of many of its constituent molecules. Organisms do all they can to minimize changes in the pH of their watery medium. An important way to do this is with buffers.

BUFFERS The maintenance of internal constancy—*homeostasis*—is a hallmark of all living things and extends to pH. As we mentioned earlier, if biological molecules lose or gain H^+ ions their properties can change, thus upsetting homeostasis. Internal constancy is achieved with buffers: solutions that maintain a relatively constant pH even when substantial amounts of acid or base are added. How does this work?

A **buffer** is a solution of a weak acid and its corresponding base—for example, carbonic acid (H_2CO_3) and bicarbonate ions (HCO_3^-). If an acid is added to a solution containing this buffer, not all the H^+ ions from the acid stay in solution. Instead, many of them combine with the bicarbonate ions to produce more carbonic acid:



This reaction uses up some of the H^+ ions in the solution and decreases the acidifying effect of the added acid. If a base is added, the reaction essentially reverses. Some of the carbonic acid

ionizes to produce bicarbonate ions and more H^+ , which counteracts some of the added base. In this way, the buffer minimizes the effect that an added acid or base has on pH. This buffering system is present in the blood, where it is important for preventing significant changes in pH that could disrupt the ability of the blood to carry vital oxygen to tissues. A given amount of acid or base causes a smaller pH change in a buffered solution than in a non-buffered one. Buffers illustrate an important chemical principle of reversible reactions, called the *law of mass action*. Addition of a reactant on one side of a reversible system drives the reaction in the

direction that uses up that compound. In the case of buffers, addition of an acid drives the reaction in one direction; addition of a base drives the reaction in the other direction. We use a buffer to relieve the common problem of indigestion. The lining of the stomach constantly secretes hydrochloric acid, making the stomach contents acidic. Excessive stomach acid inhibits digestion and causes discomfort. We can relieve this discomfort by ingesting a salt such as NaHCO_3 (“bicarbonate of soda”), which acts as a buffer.