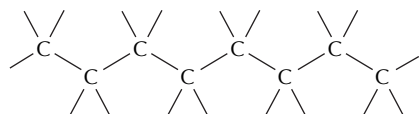


## CARBON SKELETONS

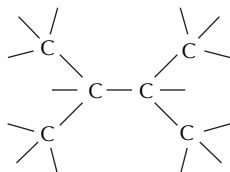
Carbon has a unique role in the cell because of its ability to form strong covalent bonds with other carbon atoms. Thus carbon atoms can join to form chains.



also written as



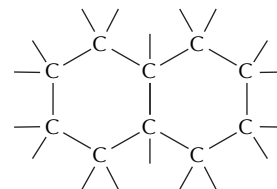
or branched trees



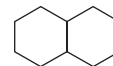
also written as



or rings



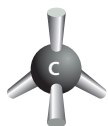
also written as



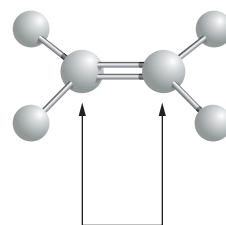
## COVALENT BONDS

A covalent bond forms when two atoms come very close together and share one or more of their electrons. In a single bond one electron from each of the two atoms is shared; in a double bond a total of four electrons are shared.

Each atom forms a fixed number of covalent bonds in a defined spatial arrangement. For example, carbon forms four single bonds arranged tetrahedrally, whereas nitrogen forms three single bonds and oxygen forms two single bonds arranged as shown below.



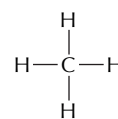
Double bonds exist and have a different spatial arrangement.



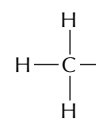
Atoms joined by two or more covalent bonds cannot rotate freely around the bond axis. This restriction is a major influence on the three-dimensional shape of many macromolecules.

## HYDROCARBONS

Carbon and hydrogen combine together to make stable compounds (or chemical groups) called hydrocarbons. These are nonpolar, do not form hydrogen bonds, and are generally insoluble in water.



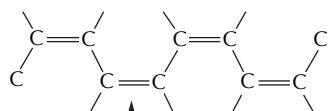
methane



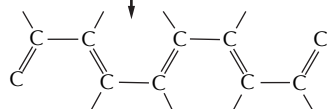
methyl group

## ALTERNATING DOUBLE BONDS

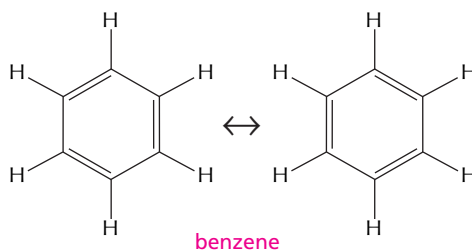
The carbon chain can include double bonds. If these are on alternate carbon atoms, the bonding electrons move within the molecule, stabilizing the structure by a phenomenon called resonance.



the truth is somewhere between these two structures

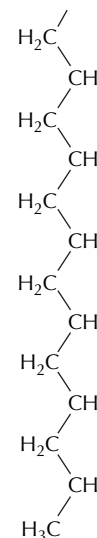


Alternating double bonds in a ring can generate a very stable structure.



benzene

often written as

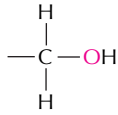


part of the hydrocarbon "tail" of a fatty acid molecule

## C-O CHEMICAL GROUPS

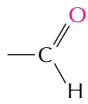
Many biological compounds contain a carbon bonded to an oxygen. For example,

alcohol

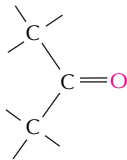


The  $-\text{OH}$  is called a **hydroxyl** group.

aldehyde

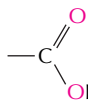


ketone



The  $\text{C}=\text{O}$  is called a **carbonyl** group.

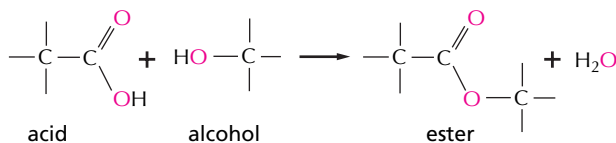
carboxylic acid



The  $-\text{COOH}$  is called a **carboxyl** group. In water this loses an  $\text{H}^+$  ion to become  $-\text{COO}^-$ .

esters

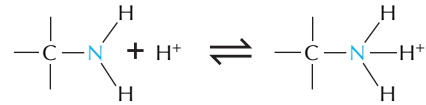
Esters are formed by a condensation reaction between acid and an alcohol.



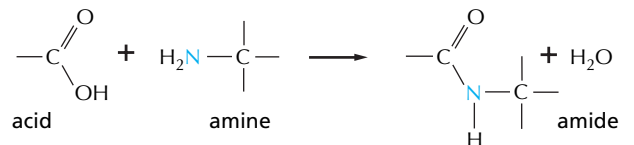
## C-N CHEMICAL GROUPS

Amines and amides are two important examples of compounds containing a carbon linked to a nitrogen.

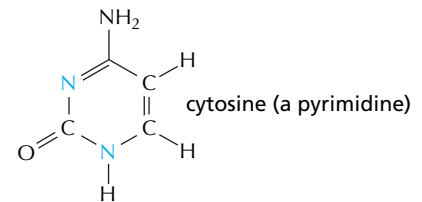
**Amines** in water combine with an  $\text{H}^+$  ion to become positively charged.



**Amides** are formed by combining an acid and an amine. Unlike amines, amides are uncharged in water. An example is the peptide bond that joins amino acids in a protein.



Nitrogen also occurs in several ring compounds, including important constituents of nucleic acids: purines and pyrimidines.



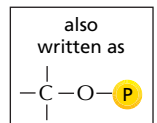
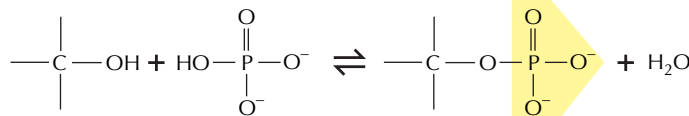
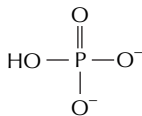
## SULFHYDRYL GROUP

The  $-\text{C}-\text{SH}$  is called a **sulfhydryl** group. In the amino acid cysteine the sulfhydryl group may exist in the reduced form,  $-\text{C}-\text{SH}$  or more rarely in an oxidized, cross-bridging form,  $-\text{C}-\text{S}-\text{S}-\text{C}-$

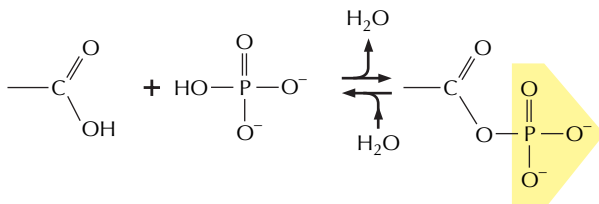
## PHOSPHATES

Inorganic phosphate is a stable ion formed from phosphoric acid,  $\text{H}_3\text{PO}_4$ . It is often written as  $\text{P}_i$ .

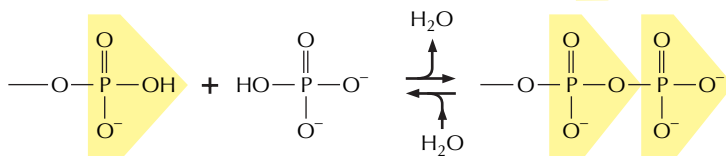
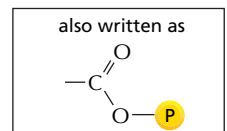
Phosphate esters can form between a phosphate and a free hydroxyl group. Phosphate groups are often attached to proteins in this way.



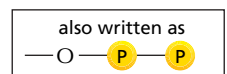
The combination of a phosphate and a carboxyl group, or two or more phosphate groups, gives an acid anhydride.



high-energy acyl phosphate bond (carboxylic-phosphoric acid anhydride) found in some metabolites

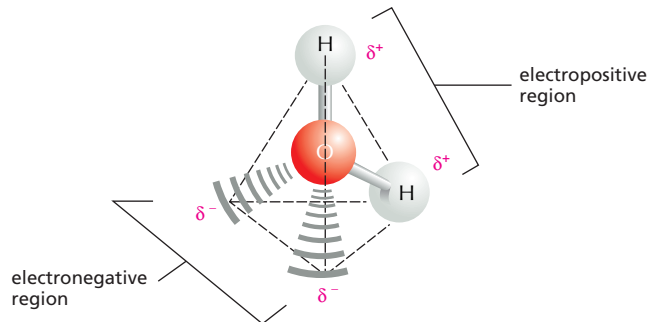


phosphoanhydride—a high-energy bond found in molecules such as ATP



## WATER

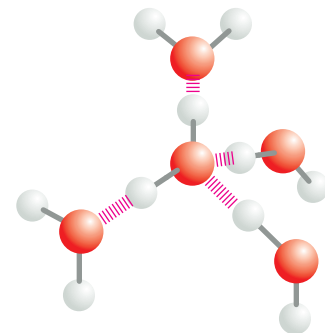
Two atoms, connected by a covalent bond, may exert different attractions for the electrons of the bond. In such cases the bond is **polar**, with one end slightly negatively charged ( $\delta^-$ ) and the other slightly positively charged ( $\delta^+$ ).



Although a water molecule has an overall neutral charge (having the same number of electrons and protons), the electrons are asymmetrically distributed, which makes the molecule polar. The oxygen nucleus draws electrons away from the hydrogen nuclei, leaving these nuclei with a small net positive charge. The excess of electron density on the oxygen atom creates weakly negative regions at the other two corners of an imaginary tetrahedron.

## WATER STRUCTURE

Molecules of water join together transiently in a hydrogen-bonded lattice. Even at 37°C, 15% of the water molecules are joined to four others in a short-lived assembly known as a "flickering cluster."

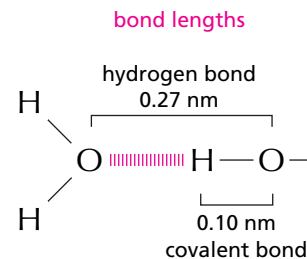
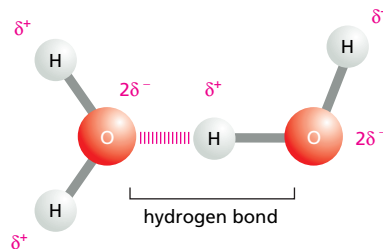


The cohesive nature of water is responsible for many of its unusual properties, such as high surface tension, specific heat, and heat of vaporization.

## HYDROGEN BONDS

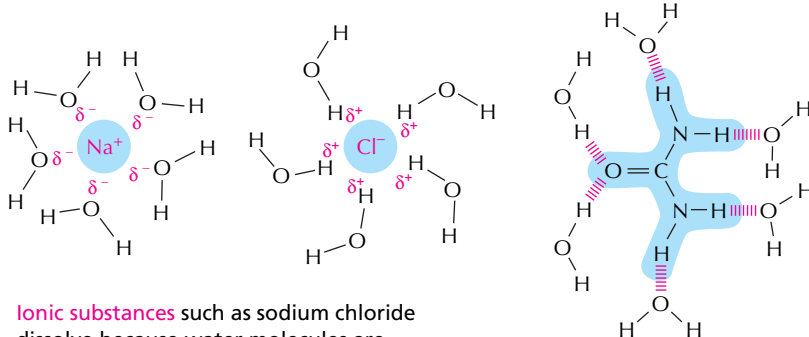
Because they are polarized, two adjacent  $\text{H}_2\text{O}$  molecules can form a linkage known as a **hydrogen bond**. Hydrogen bonds have only about 1/20 the strength of a covalent bond.

Hydrogen bonds are strongest when the three atoms lie in a straight line.



## HYDROPHILIC MOLECULES

Substances that dissolve readily in water are termed **hydrophilic**. They are composed of ions or polar molecules that attract water molecules through electrical charge effects. Water molecules surround each ion or polar molecule on the surface of a solid substance and carry it into solution.

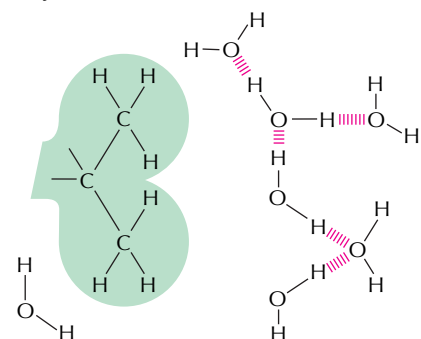


**Ionic substances** such as sodium chloride dissolve because water molecules are attracted to the positive ( $\text{Na}^+$ ) or negative ( $\text{Cl}^-$ ) charge of each ion.

**Polar substances** such as urea dissolve because their molecules form hydrogen bonds with the surrounding water molecules.

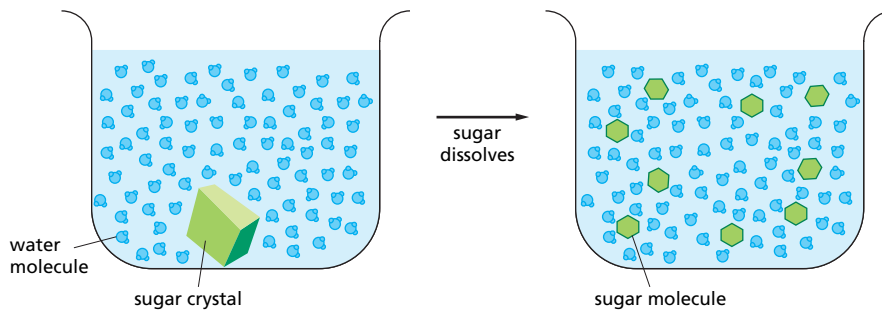
## HYDROPHOBIC MOLECULES

Molecules that contain a preponderance of nonpolar bonds are usually insoluble in water and are termed **hydrophobic**. This is true, especially, of hydrocarbons, which contain many C-H bonds. Water molecules are not attracted to such molecules and so have little tendency to surround them and carry them into solution.



## WATER AS A SOLVENT

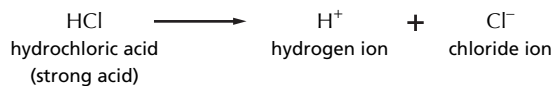
Many substances, such as household sugar, **dissolve** in water. That is, their molecules separate from each other, each becoming surrounded by water molecules.



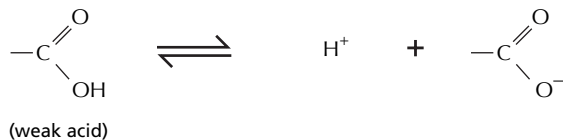
When a substance dissolves in a liquid, the mixture is termed a **solution**. The dissolved substance (in this case sugar) is the **solute**, and the liquid that does the dissolving (in this case water) is the **solvent**. Water is an excellent solvent for many substances because of its polar bonds.

## ACIDS

Substances that release hydrogen ions into solution are called **acids**.



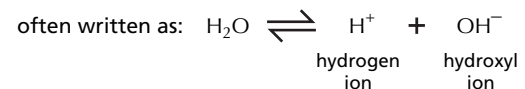
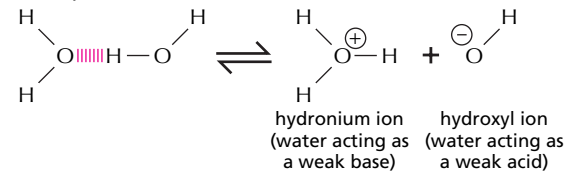
Many of the acids important in the cell are only partially dissociated, and they are therefore **weak acids**—for example, the carboxyl group ( $-\text{COOH}$ ), which dissociates to give a hydrogen ion in solution



Note that this is a reversible reaction.

## HYDROGEN ION EXCHANGE

Positively charged hydrogen ions ( $\text{H}^+$ ) can spontaneously move from one water molecule to another, thereby creating two ionic species.



Since the process is rapidly reversible, hydrogen ions are continually shuttling between water molecules. Pure water contains a steady-state concentration of hydrogen ions and hydroxyl ions (both  $10^{-7}$  M).

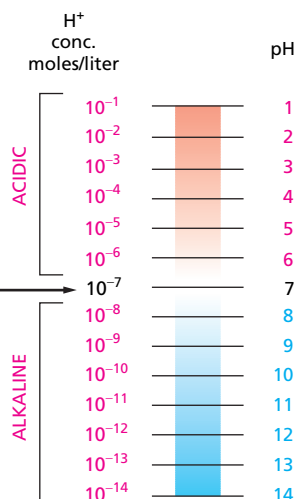
## pH

The acidity of a solution is defined by the concentration of  $\text{H}^+$  ions it possesses. For convenience we use the pH scale, where

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

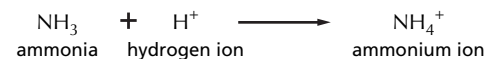
For pure water

$$[\text{H}^+] = 10^{-7} \text{ moles/liter}$$

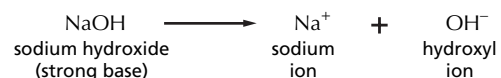


## BASES

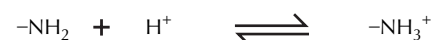
Substances that reduce the number of hydrogen ions in solution are called **bases**. Some bases, such as ammonia, combine directly with hydrogen ions.



Other bases, such as sodium hydroxide, reduce the number of  $\text{H}^+$  ions indirectly, by making  $\text{OH}^-$  ions that then combine directly with  $\text{H}^+$  ions to make  $\text{H}_2\text{O}$ .

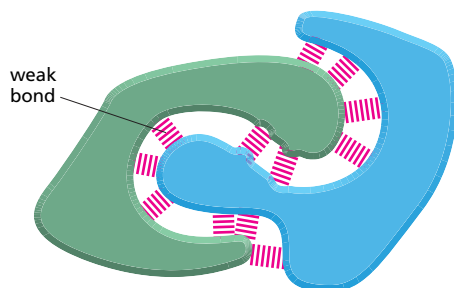


Many bases found in cells are partially dissociated and are termed **weak bases**. This is true of compounds that contain an amino group ( $-\text{NH}_2$ ), which has a weak tendency to reversibly accept an  $\text{H}^+$  ion from water, increasing the quantity of free  $\text{OH}^-$  ions.



## WEAK CHEMICAL BONDS

Organic molecules can interact with other molecules through three types of short-range attractive forces known as *noncovalent bonds*: van der Waals attractions, electrostatic attractions, and hydrogen bonds. The repulsion of hydrophobic groups from water is also important for ordering biological macromolecules.



Weak chemical bonds have less than 1/20 the strength of a strong covalent bond. They are strong enough to provide tight binding only when many of them are formed simultaneously.

## HYDROGEN BONDS

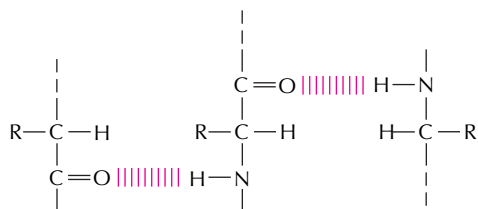
As already described for water (see Panel 2-2), **hydrogen bonds** form when a hydrogen atom is "sandwiched" between two electron-attracting atoms (usually oxygen or nitrogen).

Hydrogen bonds are strongest when the three atoms are in a straight line:

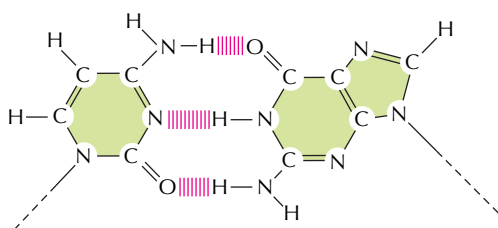


Examples in macromolecules:

Amino acids in polypeptide chains hydrogen-bonded together.

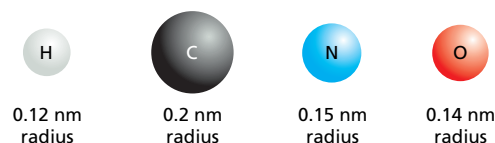


Two bases, G and C, hydrogen-bonded in DNA or RNA.



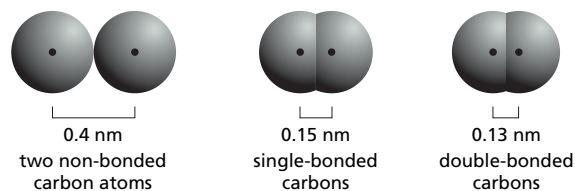
## VAN DER WAALS ATTRACTIONS

If two atoms are too close together they repel each other very strongly. For this reason, an atom can often be treated as a sphere with a fixed radius. The characteristic "size" for each atom is specified by a unique **van der Waals radius**. The contact distance between any two noncovalently bonded atoms is the sum of their van der Waals radii.



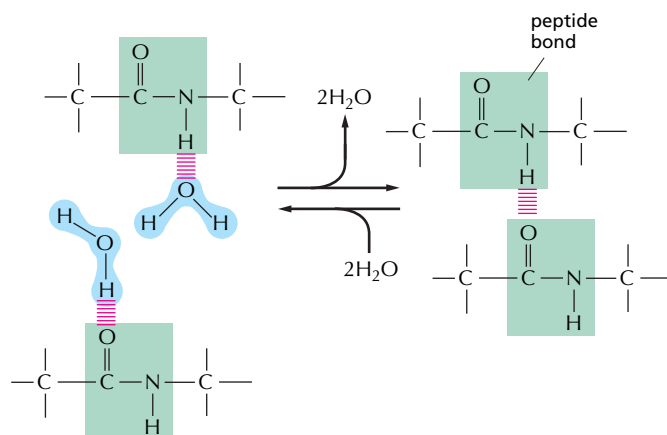
At very short distances any two atoms show a weak bonding interaction due to their fluctuating electrical charges. The two atoms will be attracted to each other in this way until the distance between their nuclei is approximately equal to the sum of their van der Waals radii. Although they are individually very weak, **van der Waals attractions** can become important when two macromolecular surfaces fit very close together, because many atoms are involved.

Note that when two atoms form a covalent bond, the centers of the two atoms (the two atomic nuclei) are much closer together than the sum of the two van der Waals radii. Thus,

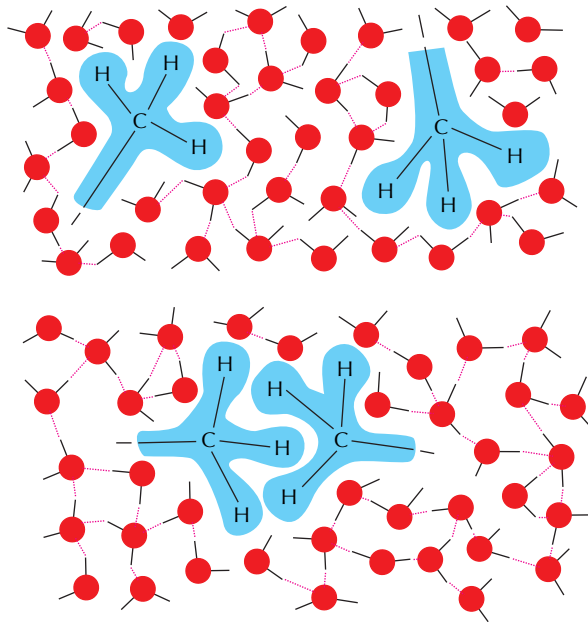


## HYDROGEN BONDS IN WATER

Any molecules that can form hydrogen bonds to each other can alternatively form hydrogen bonds to water molecules. Because of this competition with water molecules, the hydrogen bonds formed between two molecules dissolved in water are relatively weak.



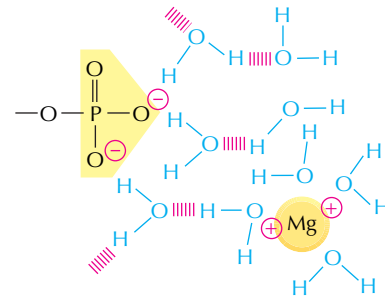
## HYDROPHOBIC FORCES



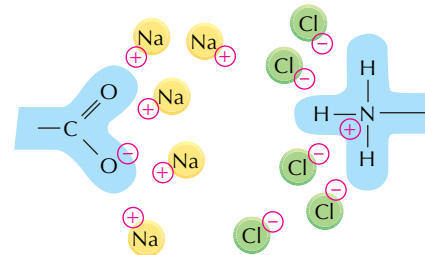
Water forces hydrophobic groups together, because doing so minimizes their disruptive effects on the hydrogen-bonded water network. Hydrophobic groups held together in this way are sometimes said to be held together by “hydrophobic bonds,” even though the apparent attraction is actually caused by a repulsion from the water.

## ELECTROSTATIC ATTRACTIONS IN AQUEOUS SOLUTIONS

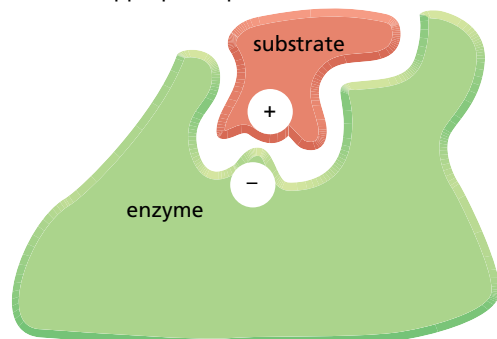
Charged groups are shielded by their interactions with water molecules. Electrostatic attractions are therefore quite weak in water.



Similarly, ions in solution can cluster around charged groups and further weaken these attractions.



Despite being weakened by water and salt, electrostatic attractions are very important in biological systems. For example, an enzyme that binds a positively charged substrate will often have a negatively charged amino acid side chain at the appropriate place.



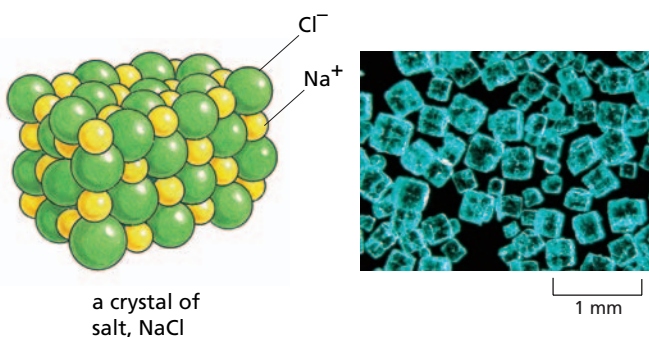
## ELECTROSTATIC ATTRACTIONS

Attractive forces occur both between fully charged groups (ionic bond) and between the partially charged groups on polar molecules.



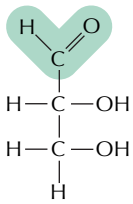
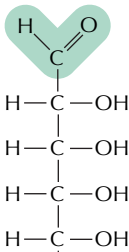
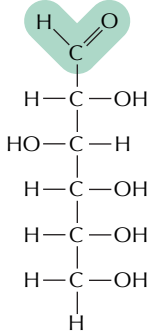
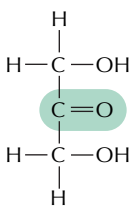
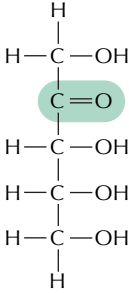
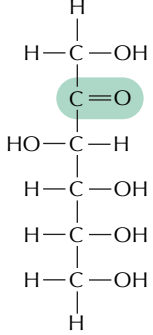
The force of attraction between the two charges,  $\delta^+$  and  $\delta^-$ , falls off rapidly as the distance between the charges increases.

In the absence of water, electrostatic forces are very strong. They are responsible for the strength of such minerals as marble and agate, and for crystal formation in common table salt, NaCl.



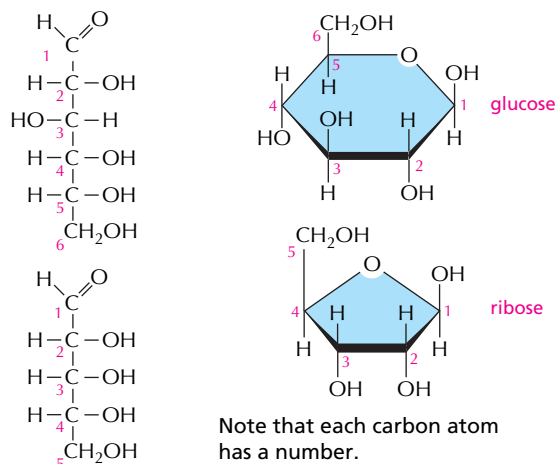
## MONOSACCHARIDES

Monosaccharides usually have the general formula  $(\text{CH}_2\text{O})_n$ , where  $n$  can be 3, 4, 5, 6, 7, or 8, and have two or more hydroxyl groups. They either contain an aldehyde group ( $-\text{C}(=\text{O})\text{H}$ ) and are called aldoses or a ketone group ( $>\text{C}=\text{O}$ ) and are called ketoses.

	3-carbon (TRIOSES)	5-carbon (PENTOSES)	6-carbon (HEXOSEs)
ALDOSES	 <p>glyceraldehyde</p>	 <p>ribose</p>	 <p>glucose</p>
KETOSES	 <p>dihydroxyacetone</p>	 <p>ribulose</p>	 <p>fructose</p>

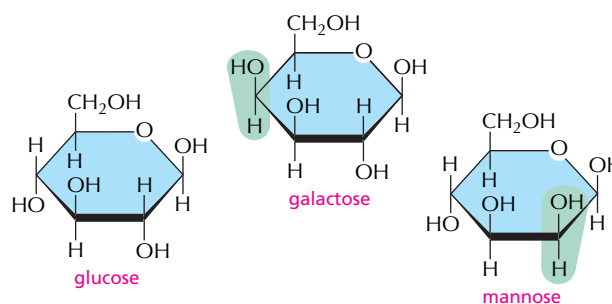
## RING FORMATION

In aqueous solution, the aldehyde or ketone group of a sugar molecule tends to react with a hydroxyl group of the same molecule, thereby closing the molecule into a ring.



## ISOMERS

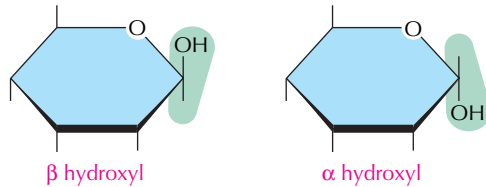
Many monosaccharides differ only in the spatial arrangement of atoms—that is, they are **isomers**. For example, glucose, galactose, and mannose have the same formula ( $\text{C}_6\text{H}_{12}\text{O}_6$ ) but differ in the arrangement of groups around one or two carbon atoms.



These small differences make only minor changes in the chemical properties of the sugars. But they are recognized by enzymes and other proteins and therefore can have important biological effects.

**$\alpha$  AND  $\beta$  LINKS**

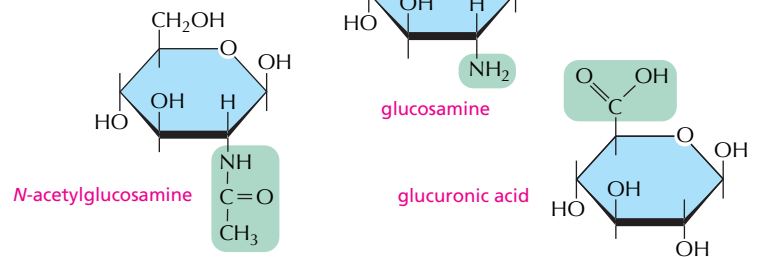
The hydroxyl group on the carbon that carries the aldehyde or ketone can rapidly change from one position to the other. These two positions are called  $\alpha$  and  $\beta$ .



As soon as one sugar is linked to another, the  $\alpha$  or  $\beta$  form is frozen.

**SUGAR DERIVATIVES**

The hydroxyl groups of a simple monosaccharide can be replaced by other groups. For example,

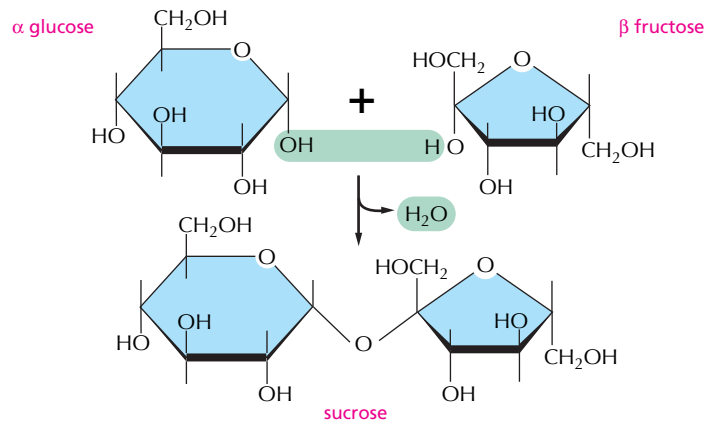
**DISACCHARIDES**

The carbon that carries the aldehyde or the ketone can react with any hydroxyl group on a second sugar molecule to form a **disaccharide**. The linkage is called a glycosidic bond.

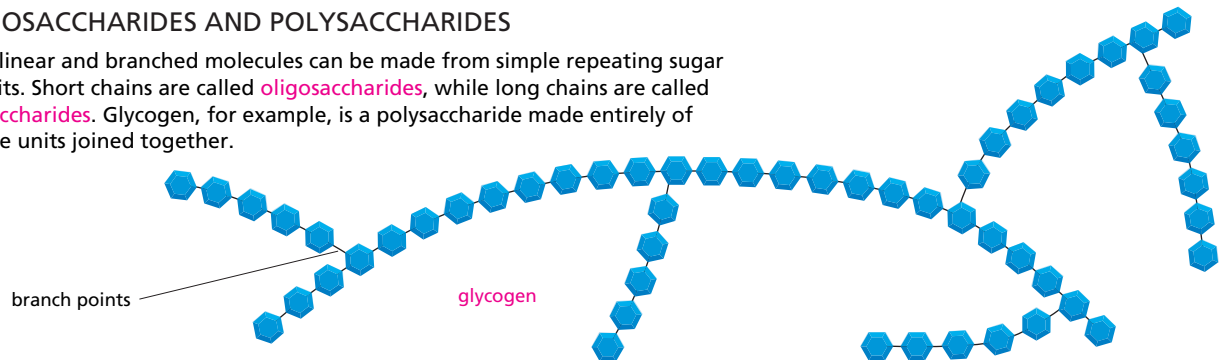
Three common disaccharides are

- maltose (glucose + glucose)
- lactose (galactose + glucose)
- sucrose (glucose + fructose)

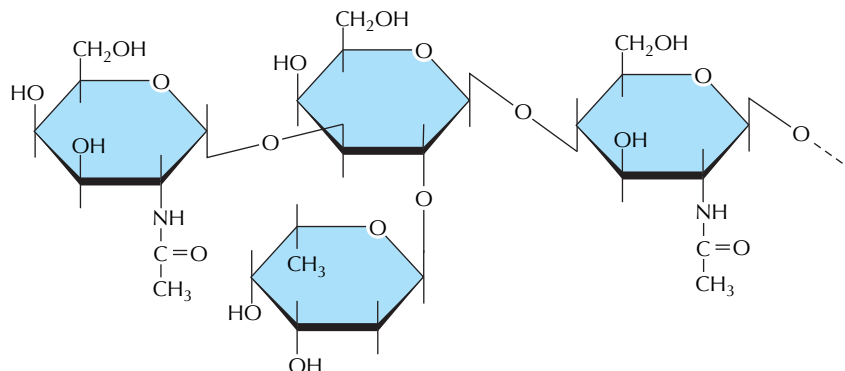
The reaction forming sucrose is shown here.

**OLIGOSACCHARIDES AND POLYSACCHARIDES**

Large linear and branched molecules can be made from simple repeating sugar subunits. Short chains are called **oligosaccharides**, while long chains are called **polysaccharides**. Glycogen, for example, is a polysaccharide made entirely of glucose units joined together.

**COMPLEX OLIGOSACCHARIDES**

In many cases a sugar sequence is nonrepetitive. Many different molecules are possible. Such complex oligosaccharides are usually linked to proteins or to lipids, as is this oligosaccharide, which is part of a cell-surface molecule that defines a particular blood group.





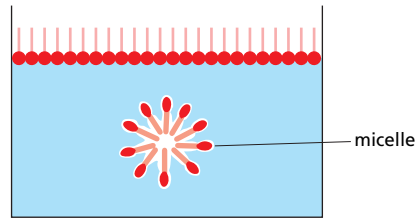


## LIPID AGGREGATES

Fatty acids have a hydrophilic head and a hydrophobic tail.

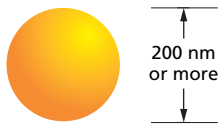


In water they can form a surface film or form small micelles.

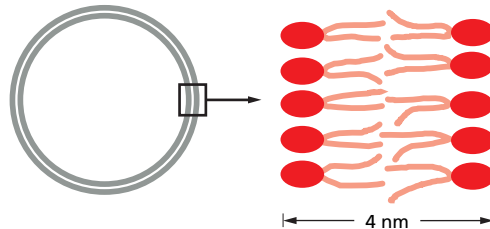


Their derivatives can form larger aggregates held together by hydrophobic forces:

**Triglycerides** can form large spherical fat droplets in the cell cytoplasm.

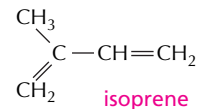


**Phospholipids** and **glycolipids** form self-sealing lipid bilayers that are the basis for all cell membranes.



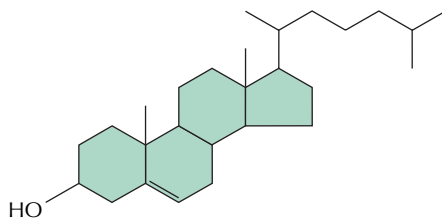
## OTHER LIPIDS

Lipids are defined as the water-insoluble molecules in cells that are soluble in organic solvents. Two other common types of lipids are steroids and polyisoprenoids. Both are made from isoprene units.

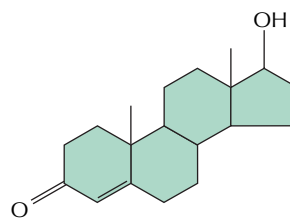


## STERIODS

Steroids have a common multiple-ring structure.



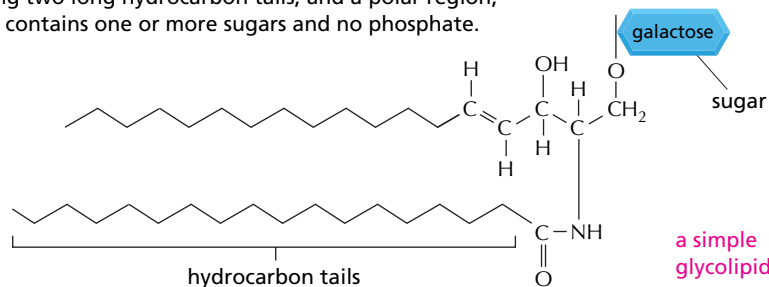
**cholesterol**—found in many membranes



**testosterone**—male steroid hormone

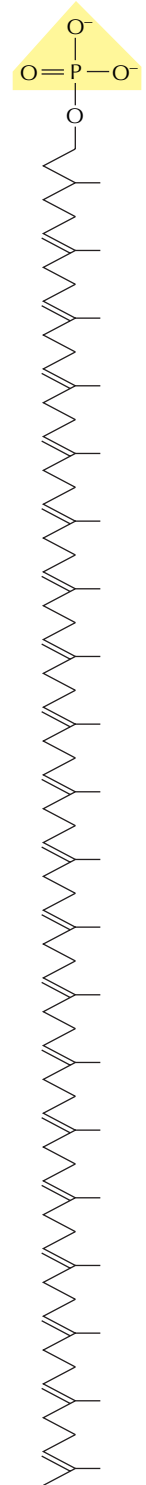
## GLYCOLIPIDS

Like phospholipids, these compounds are composed of a hydrophobic region, containing two long hydrocarbon tails, and a polar region, which, however, contains one or more sugars and no phosphate.



## POLYISOPRENOIDS

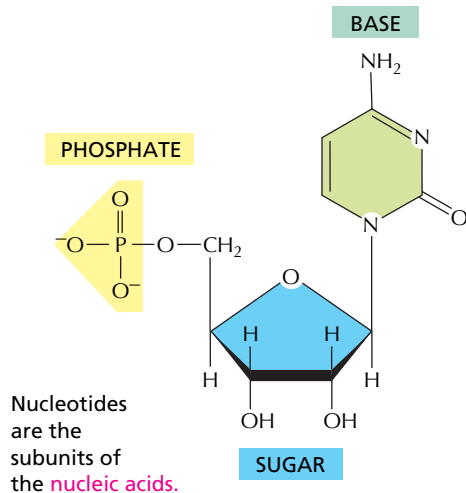
long-chain polymers of isoprene



**dolichol phosphate**—used to carry activated sugars in the membrane-associated synthesis of glycoproteins and some polysaccharides

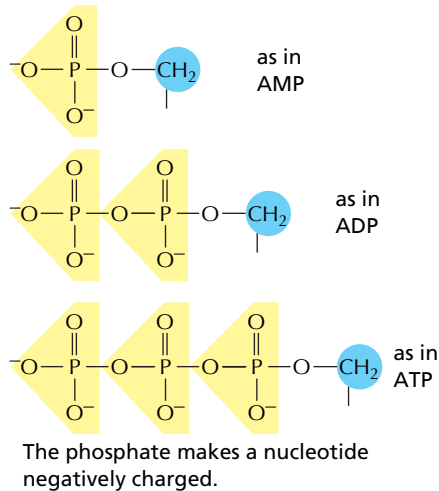
## NUCLEOTIDES

A nucleotide consists of a nitrogen-containing base, a five-carbon sugar, and one or more phosphate groups.

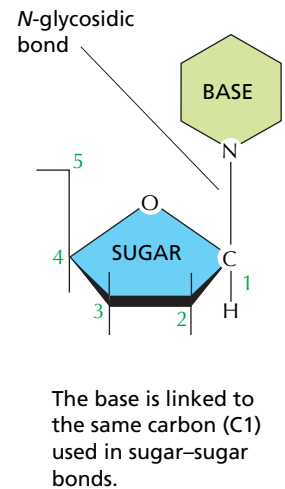


## PHOSPHATES

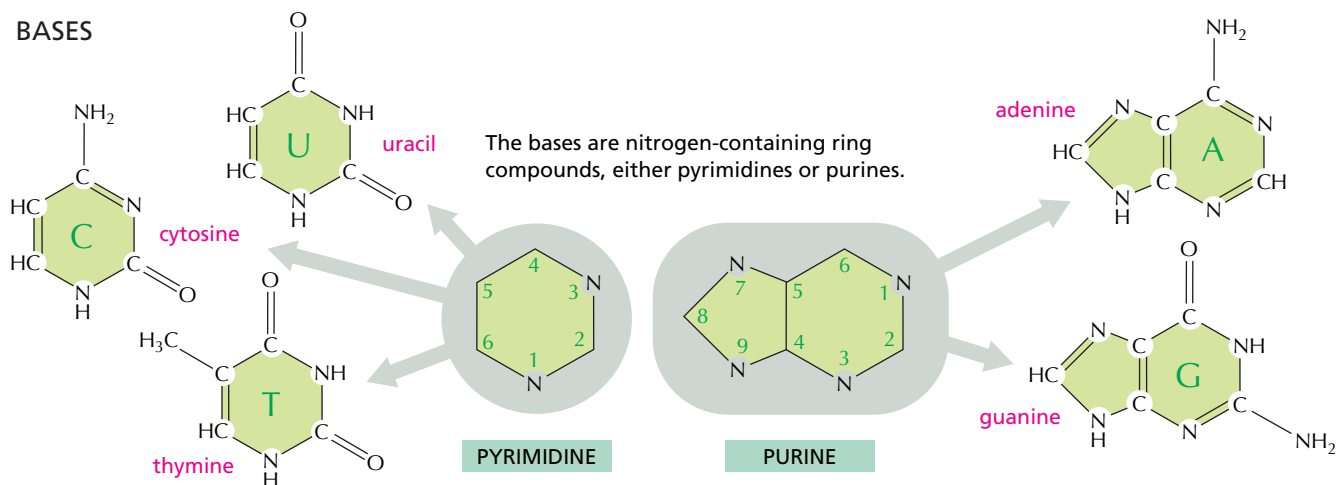
The phosphates are normally joined to the C5 hydroxyl of the ribose or deoxyribose sugar (designated 5'). Mono-, di-, and triphosphates are common.



## BASIC SUGAR LINKAGE

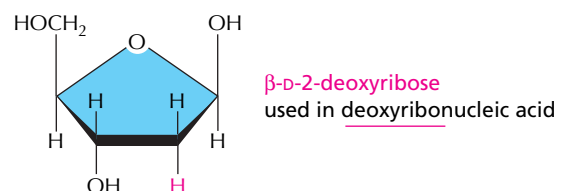
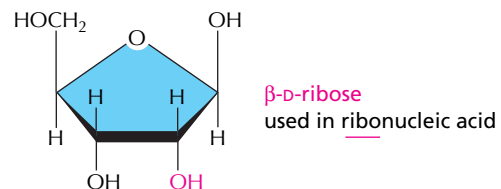
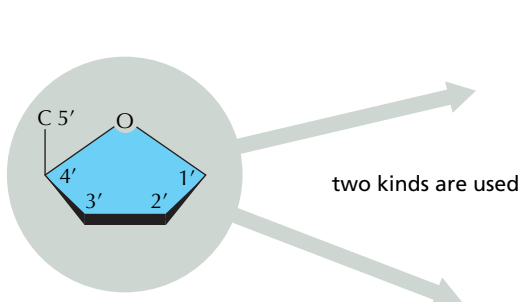


## BASES



## SUGARS

**PENTOSE**  
a five-carbon sugar



Each numbered carbon on the sugar of a nucleotide is followed by a prime mark; therefore, one speaks of the "5-prime carbon," etc.

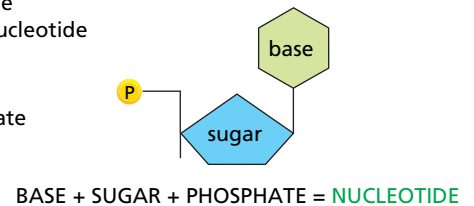
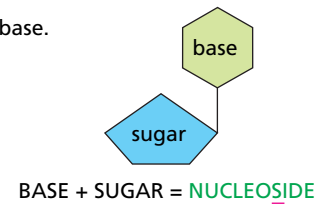
## NOMENCLATURE

A nucleoside or nucleotide is named according to its nitrogenous base.

BASE	NUCLEOSIDE	ABBR.
adenine	adenosine	<b>A</b>
guanine	guanosine	<b>G</b>
cytosine	cytidine	<b>C</b>
uracil	uridine	<b>U</b>
thymine	thymidine	<b>T</b>

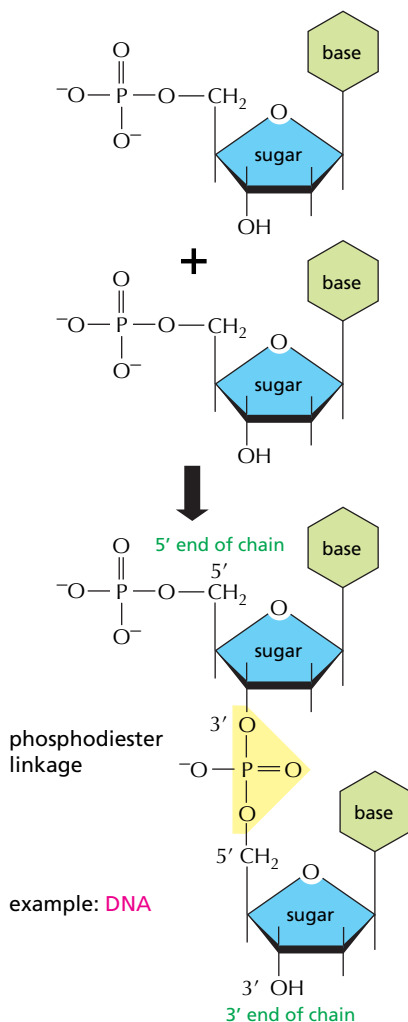
Single letter abbreviations are used variously as shorthand for (1) the base alone, (2) the nucleoside, or (3) the whole nucleotide—the context will usually make clear which of the three entities is meant. When the context is not sufficient, we will add the terms “base”, “nucleoside”, “nucleotide”, or—as in the examples below—use the full 3-letter nucleotide code.

AMP = adenosine monophosphate  
 dAMP = deoxyadenosine monophosphate  
 UDP = uridine diphosphate  
 ATP = adenosine triphosphate



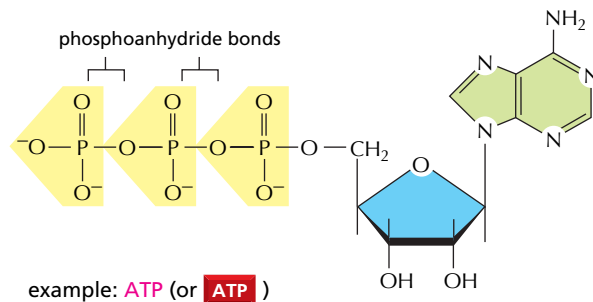
## NUCLEIC ACIDS

Nucleotides are joined together by a **phosphodiester linkage** between 5' and 3' carbon atoms to form nucleic acids. The linear sequence of nucleotides in a nucleic acid chain is commonly abbreviated by a one-letter code, A—G—C—T—T—A—C—A, with the 5' end of the chain at the left.

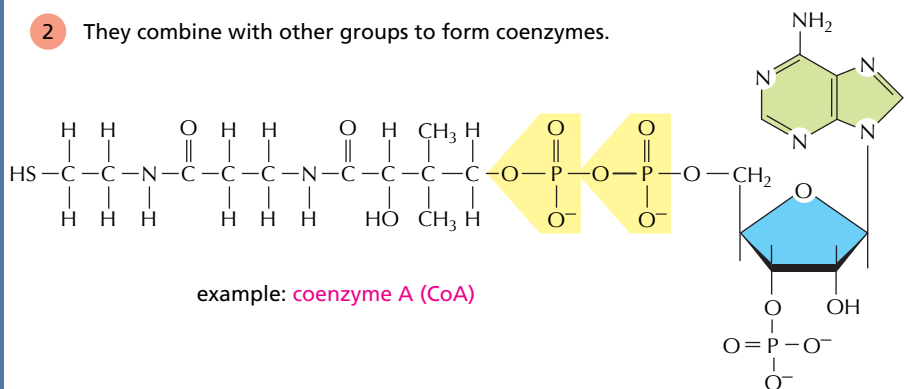


## NUCLEOTIDES HAVE MANY OTHER FUNCTIONS

- 1 They carry chemical energy in their easily hydrolyzed phosphoanhydride bonds.

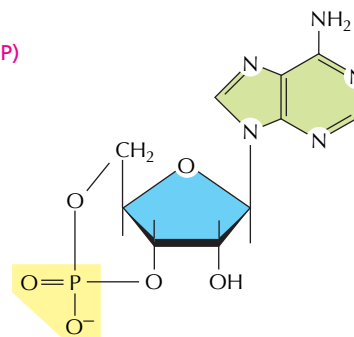


- 2 They combine with other groups to form coenzymes.



- 3 They are used as specific signaling molecules in the cell.

example: **cyclic AMP (cAMP)**

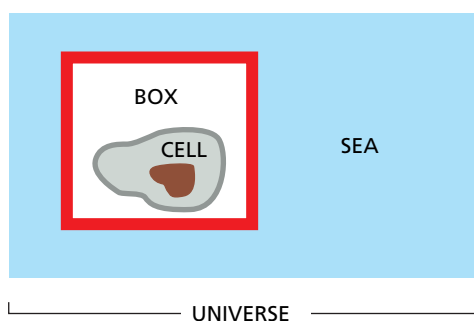


## THE IMPORTANCE OF FREE ENERGY FOR CELLS

Life is possible because of the complex network of interacting chemical reactions occurring in every cell. In viewing the metabolic pathways that comprise this network, one might suspect that the cell has had the ability to evolve an enzyme to carry out any reaction that it needs. But this is not so. Although enzymes are powerful catalysts, they can speed up only those reactions that are thermodynamically possible; other reactions proceed in cells only because they are *coupled* to very favorable reactions that drive them. The question of whether a reaction

can occur spontaneously, or instead needs to be coupled to another reaction, is central to cell biology. The answer is obtained by reference to a quantity called the *free energy*: the total change in free energy during a set of reactions determines whether or not the entire reaction sequence can occur. In this panel we shall explain some of the fundamental ideas—derived from a special branch of chemistry and physics called *thermodynamics*—that are required for understanding what free energy is and why it is so important to cells.

## ENERGY RELEASED BY CHANGES IN CHEMICAL BONDING IS CONVERTED INTO HEAT



An *enclosed system* is defined as a collection of molecules that does not exchange matter with the rest of the universe (for example, the “cell in a box” shown above). Any such system will contain molecules with a total energy  $E$ . This energy will be distributed in a variety of ways: some as the translational energy of the molecules, some as their vibrational and rotational energies, but most as the bonding energies between the individual atoms that make up the molecules. Suppose that a reaction occurs in the system. The **first law of thermodynamics** places a constraint on what types of reactions are possible: it states that “**in any process, the total energy of the universe remains constant.**” For example, suppose that reaction  $A \rightarrow B$  occurs somewhere in the box and releases a great deal of chemical bond energy. This energy will initially increase the intensity of molecular motions (translational, vibrational, and rotational) in the system, which is equivalent to raising its temperature. However, these increased motions will soon be transferred out of the system by a series

of molecular collisions that heat up first the walls of the box and then the outside world (represented by the sea in our example). In the end, the system returns to its initial temperature, by which time all the chemical bond energy released in the box has been converted into heat energy and transferred out of the box to the surroundings. According to the first law, the change in the energy in the box ( $\Delta E_{\text{box}}$ , which we shall denote as  $\Delta E$ ) must be equal and opposite to the amount of heat energy transferred, which we shall designate as  $h$ : that is,  $\Delta E = -h$ . Thus, the energy in the box ( $E$ ) decreases when heat leaves the system.

$E$  also can change during a reaction as a result of work being done on the outside world. For example, suppose that there is a small increase in the volume ( $\Delta V$ ) of the box during a reaction. Since the walls of the box must push against the constant pressure ( $P$ ) in the surroundings in order to expand, this does work on the outside world and requires energy. The energy used is  $P(\Delta V)$ , which according to the first law must decrease the energy in the box ( $E$ ) by the same amount. In most reactions chemical bond energy is converted into both work and heat. *Enthalpy* ( $H$ ) is a composite function that includes both of these ( $H = E + PV$ ). To be rigorous, it is the change in enthalpy ( $\Delta H$ ) in an enclosed system, and not the change in energy, that is equal to the heat transferred to the outside world during a reaction. Reactions in which  $H$  decreases release heat to the surroundings and are said to be “exothermic,” while reactions in which  $H$  increases absorb heat from the surroundings and are said to be “endothermic.” Thus,  $-h = \Delta H$ . However, the volume change is negligible in most biological reactions, so to a good approximation

$$-h = \Delta H \cong \Delta E$$

## THE SECOND LAW OF THERMODYNAMICS

Consider a container in which 1000 coins are all lying heads up. If the container is shaken vigorously, subjecting the coins to the types of random motions that all molecules experience due to their frequent collisions with other molecules, one will end up with about half the coins oriented heads down. The reason for this reorientation is that there is only a single way in which the original orderly state of the coins can be reinstated (every coin must lie heads up), whereas there are many different ways (about  $10^{298}$ ) to achieve a disorderly state in which there is an equal mixture of heads and tails; in fact, there are more ways

to achieve a 50-50 state than to achieve any other state. Each state has a probability of occurrence that is proportional to the number of ways it can be realized. The **second law of thermodynamics** states that “**systems will change spontaneously from states of lower probability to states of higher probability.**” Since states of lower probability are more “ordered” than states of high probability, the second law can be restated: “the universe constantly changes so as to become more disordered.”

## THE ENTROPY, $S$

The second law (but not the first law) allows one to predict the *direction* of a particular reaction. But to make it useful for this purpose, one needs a convenient measure of the probability or, equivalently, the degree of disorder of a state. The entropy ( $S$ ) is such a measure. It is a logarithmic function of the probability such that the *change in entropy* ( $\Delta S$ ) that occurs when the reaction  $A \rightarrow B$  converts one mole of A into one mole of B is

$$\Delta S = R \ln p_B / p_A$$

where  $p_A$  and  $p_B$  are the probabilities of the two states A and B,  $R$  is the gas constant ( $2 \text{ cal deg}^{-1} \text{ mole}^{-1}$ ), and  $\Delta S$  is measured in entropy units (eu). In our initial example of 1000 coins, the relative probability of all heads (state A) versus half heads and half tails (state B) is equal to the ratio of the number of different ways that the two results can be obtained. One can calculate that  $p_A = 1$  and  $p_B = 1000!(500! \times 500!) = 10^{299}$ . Therefore, the entropy change for the reorientation of the coins when their

container is vigorously shaken and an equal mixture of heads and tails is obtained is  $R \ln (10^{298})$ , or about 1370 eu per mole of such containers ( $6 \times 10^{23}$  containers). We see that, because  $\Delta S$  defined above is positive for the transition from state A to state B ( $p_B/p_A > 1$ ), reactions with a large *increase* in  $S$  (that is, for which  $\Delta S > 0$ ) are favored and will occur spontaneously.

As discussed in Chapter 2, heat energy causes the random commotion of molecules. Because the transfer of heat from an enclosed system to its surroundings increases the number of different arrangements that the molecules in the outside world can have, it increases their entropy. It can be shown that the release of a fixed quantity of heat energy has a greater disordering effect at low temperature than at high temperature, and that the value of  $\Delta S$  for the surroundings, as defined above ( $\Delta S_{\text{sea}}$ ), is precisely equal to  $h$ , the amount of heat transferred to the surroundings from the system, divided by the absolute temperature ( $T$ ):

$$\Delta S_{\text{sea}} = h / T$$

## THE GIBBS FREE ENERGY, $G$

When dealing with an enclosed biological system, one would like to have a simple way of predicting whether a given reaction will or will not occur spontaneously in the system. We have seen that the crucial question is whether the entropy change for the universe is positive or negative when that reaction occurs. In our idealized system, the cell in a box, there are two separate components to the entropy change of the universe—the entropy change for the system enclosed in the box and the entropy change for the surrounding “sea”—and both must be added together before any prediction can be made. For example, it is possible for a reaction to absorb heat and thereby decrease the entropy of the sea ( $\Delta S_{\text{sea}} < 0$ ) and at the same time to cause such a large degree of disordering inside the box ( $\Delta S_{\text{box}} > 0$ ) that the total  $\Delta S_{\text{universe}} = \Delta S_{\text{sea}} + \Delta S_{\text{box}}$  is greater than 0. In this case the reaction will occur spontaneously, even though the sea gives up heat to the box during the reaction. An example of such a reaction is the dissolving of sodium chloride in a beaker containing water (the “box”), which is a spontaneous process even though the temperature of the water drops as the salt goes into solution.

Chemists have found it useful to define a number of new “composite functions” that describe *combinations* of physical properties of a system. The properties that can be combined include the temperature ( $T$ ), pressure ( $P$ ), volume ( $V$ ), energy ( $E$ ), and entropy ( $S$ ). The enthalpy ( $H$ ) is one such composite function. But by far the most useful composite function for biologists is the *Gibbs free energy*,  $G$ . It serves as an accounting device that allows one to deduce the entropy change of the universe resulting from a chemical reaction in the box, while avoiding any separate consideration of the entropy change in the sea. The definition of  $G$  is

$$G = H - TS$$

where, for a box of volume  $V$ ,  $H$  is the enthalpy described above ( $E + PV$ ),  $T$  is the absolute temperature, and  $S$  is the entropy. Each of these quantities applies to the inside of the box only. The change in free energy during a reaction in the box (the  $G$  of the products minus the  $G$  of the starting materials) is denoted as  $\Delta G$  and, as we shall now demonstrate, it is a direct measure of the amount of disorder that is created in the universe when the reaction occurs.

At constant temperature the change in free energy ( $\Delta G$ ) during a reaction equals  $\Delta H - T\Delta S$ . Remembering that  $\Delta H = -h$ , the heat absorbed from the sea, we have

$$-\Delta G = -\Delta H + T\Delta S$$

$$-\Delta G = h + T\Delta S, \text{ so } -\Delta G/T = h/T + \Delta S$$

But  $h/T$  is equal to the entropy change of the sea ( $\Delta S_{\text{sea}}$ ), and the  $\Delta S$  in the above equation is  $\Delta S_{\text{box}}$ . Therefore

$$-\Delta G/T = \Delta S_{\text{sea}} + \Delta S_{\text{box}} = \Delta S_{\text{universe}}$$

We conclude that **the free-energy change is a direct measure of the entropy change of the universe**. A reaction will proceed in the direction that causes the change in the free energy ( $\Delta G$ ) to be less than zero, because in this case there will be a positive entropy change in the universe when the reaction occurs.

For a complex set of coupled reactions involving many different molecules, the total free-energy change can be computed simply by adding up the free energies of all the different molecular species after the reaction and comparing this value with the sum of free energies before the reaction; for common substances the required free-energy values can be found from published tables. In this way one can predict the direction of a reaction and thereby readily check the feasibility of any proposed mechanism. Thus, for example, from the observed values for the magnitude of the electrochemical proton gradient across the inner mitochondrial membrane and the  $\Delta G$  for ATP hydrolysis inside the mitochondrion, one can be certain that ATP synthase requires the passage of more than one proton for each molecule of ATP that it synthesizes.

**The value of  $\Delta G$  for a reaction is a direct measure of how far the reaction is from equilibrium.** The large negative value for ATP hydrolysis in a cell merely reflects the fact that cells keep the ATP hydrolysis reaction as much as 10 orders of magnitude away from equilibrium. If a reaction reaches equilibrium,  $\Delta G = 0$ , the reaction then proceeds at precisely equal rates in the forward and backward direction. For ATP hydrolysis, equilibrium is reached when the vast majority of the ATP has been hydrolyzed, as occurs in a dead cell.