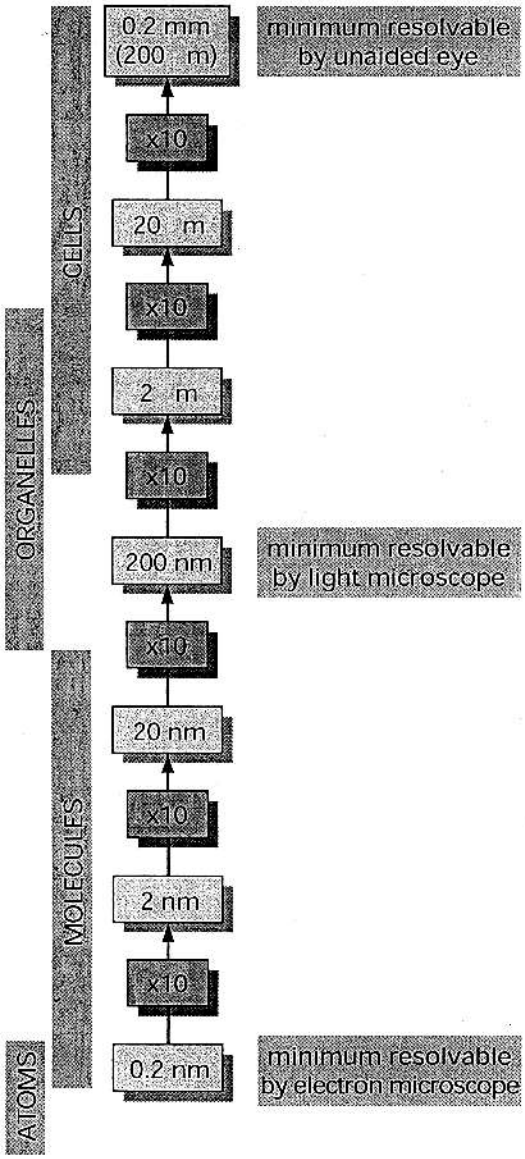
## Relative Sizes

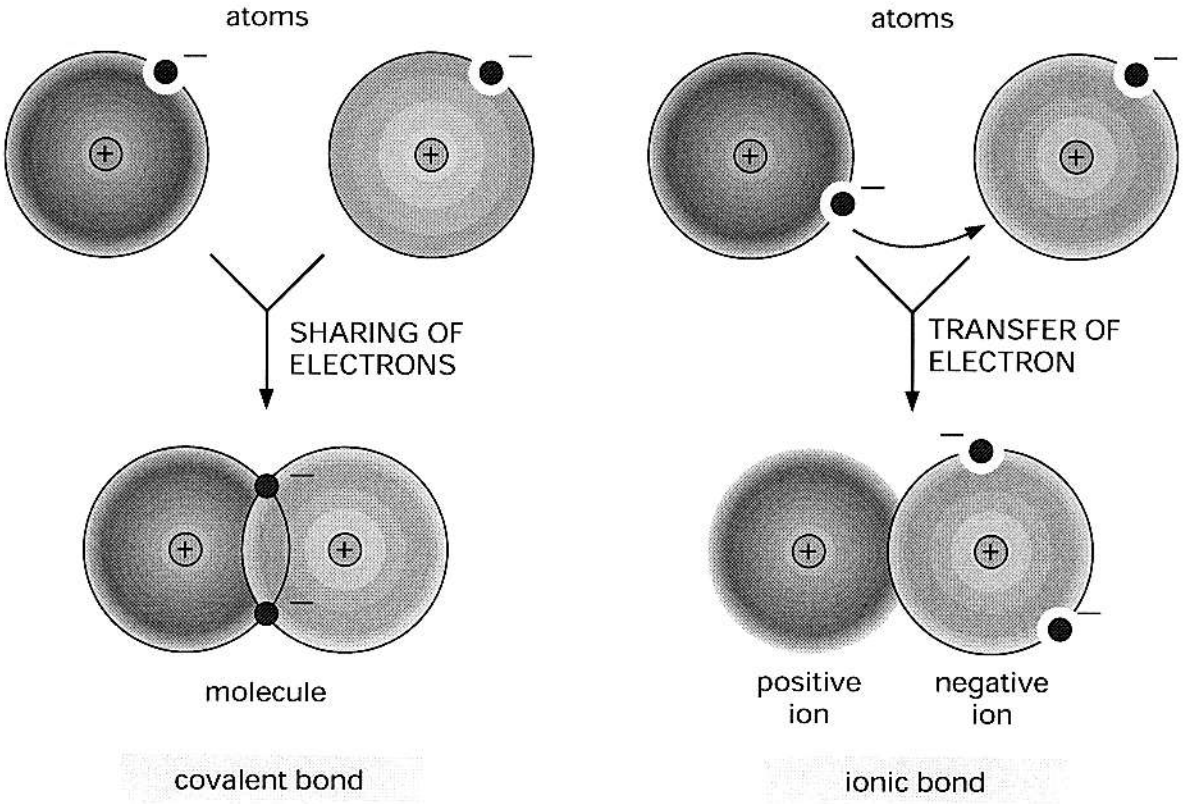





$$1\ \text{m} = 10^3\ \text{mm} = 10^6\ \text{m} = 10^9\ \text{nm}$$

## Covalent and Ionic Bonds



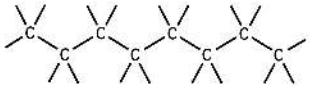


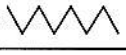
# Chemical Bonds and Groups - Part 1



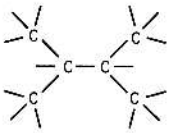
## CARBON SKELETONS

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.



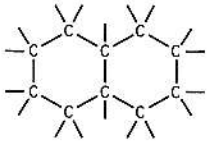
also written as 

or branched trees



also written as 

or rings



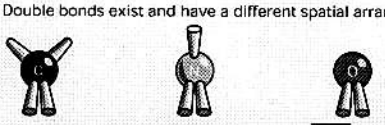
also written as 

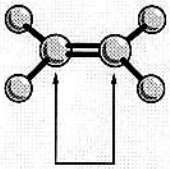
## COVALENT BONDS

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.





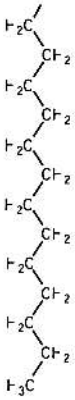
Atoms joined by two or more covalent bonds cannot rotate freely around the bond axis. This restriction is a major influence on the three-dimensional shape of many macromolecules.

## C–H COMPOUNDS

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

methane

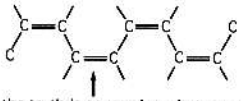
methyl group



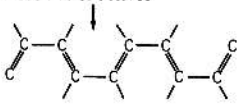
part of the hydrocarbon "tail" of a fatty acid molecule

## ALTERNATING DOUBLE BONDS

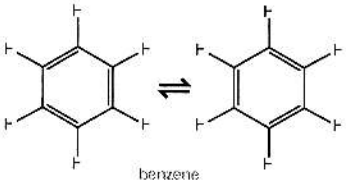
The carbon chain can include double bonds. If these are on alternate carbon atoms, the bonding electrons move within the molecule, stabilizing the structure by a phenomenon called resonance.



the truth is somewhere between these two structures



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



benzene

often written as 

# Chemical Bonds and Groups - Part 2



## C–O COMPOUNDS

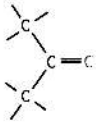
Many biological compounds contain a carbon bonded to an oxygen. For example,

alcohol

The –OH is called a hydroxyl group.

aldehyde

ketone



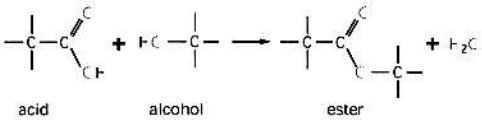
The C=O is called a carbonyl group.

carboxylic acid

The –COOH is called a carboxyl group. In water this loses an $H^+$ ion to become $-COO^-$.

esters

Esters are formed by combining an acid and an alcohol.

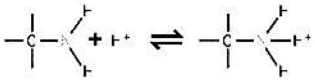


acid alcohol ester

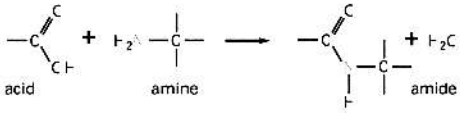
## C–N COMPOUNDS

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

Amines in water combine with an $H^+$ ion to become positively charged.

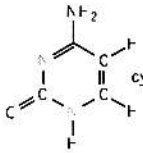


Amides are formed by combining an acid and an amine. Unlike amines, amides are uncharged in water. An example is the peptide bond that joins amino acids in a protein.



acid amine amide

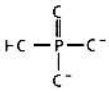
Nitrogen also occurs in several ring compounds, including important constituents of nucleic acids: purines and pyrimidines.



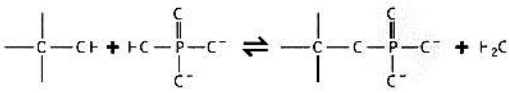
cytosine (a pyrimidine)

## PHOSPHATES

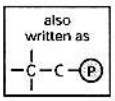
Inorganic phosphate is a stable ion formed from phosphoric acid, $H_3PO_4$. It is often written as $P_i$.



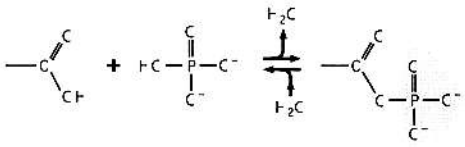
Phosphate esters can form between a phosphate and a free hydroxyl group. Phosphate groups are often attached to proteins in this way.



also written as

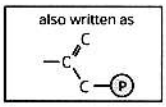


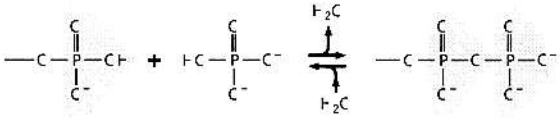
The combination of a phosphate and a carboxyl group, or two or more phosphate groups, gives an acid anhydride.



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

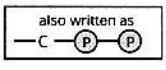
also written as





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

also written as

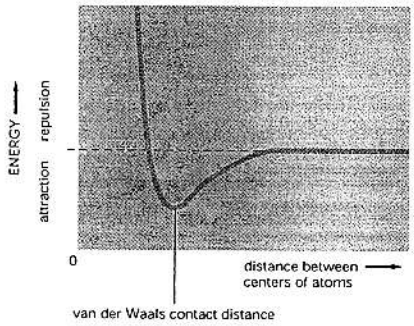


# Types of Weak Non-covalent Bonds - Part 1



## VAN DER WAALS FORCES

At very short distances any two atoms show a weak bonding interaction due to their fluctuating electrical charges. If the two atoms are too close together, however, they repel each other very strongly.

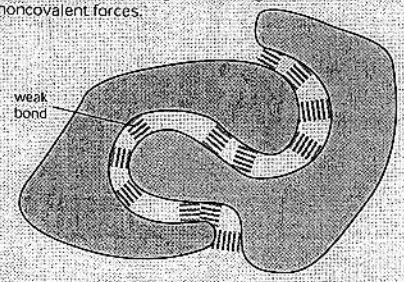



Each atom has a characteristic "size," or van der Waals radius: the contact distance between any two atoms is the sum of their van der Waals radii.


Two atoms will be attracted to each other by van der Waals forces until the distance between them equals 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.

## WEAK CHEMICAL BONDS

Organic molecules can interact with other molecules through short-range noncovalent forces.




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.

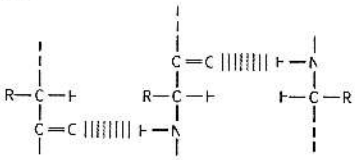
## HYDROGEN BONDS

As already described for water (see Panel 2–2, pp. 50–51) hydrogen bonds form when a hydrogen atom is "sandwiched" between two electron-attracting atoms (usually oxygen or nitrogen).

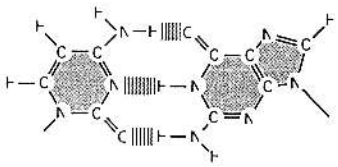
Hydrogen bonds are strongest when the three atoms are in a straight line:

Examples in macromolecules:

Amino acids in polypeptide chains hydrogen-bonded together.

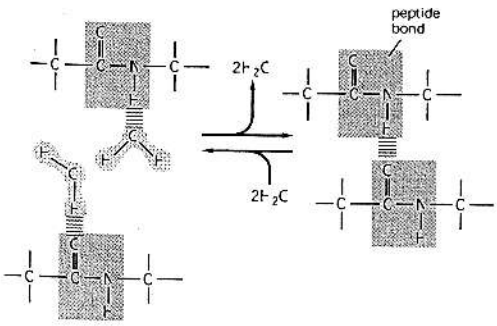


Two bases, G and C, hydrogen-bonded in DNA or RNA.



## HYDROGEN BONDS IN WATER

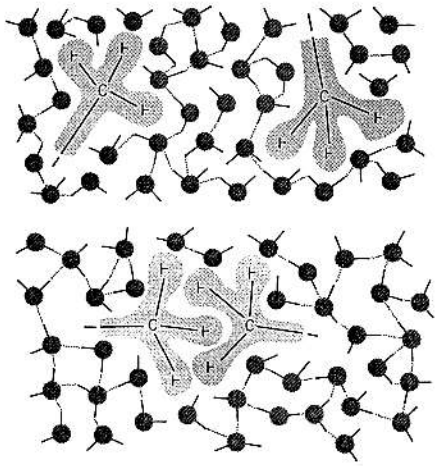
Any molecules that can form hydrogen bonds to each other can alternatively form hydrogen bonds to water molecules. Because of this competition with water molecules, the hydrogen bonds formed between two molecules dissolved in water are relatively weak.



# Types of Weak Non-covalent Bonds - Part 2



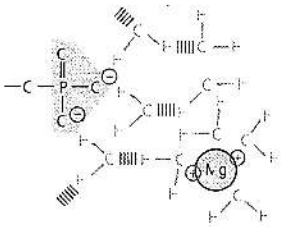
## HYDROPHOBIC FORCES



Water forces hydrophobic groups together in order to minimize 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 attraction is actually caused by a repulsion from the water.

## IONIC BONDS IN AQUEOUS SOLUTIONS

Charged groups are shielded by their interactions with water molecules. Ionic bonds are therefore quite weak in water.



## IONIC BONDS

Ionic interactions occur either between fully charged groups (ionic bond) or between partially charged groups.

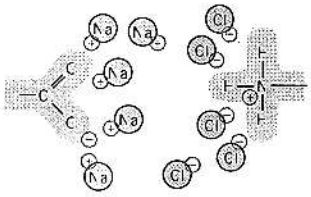
The force of attraction between the two charges, "+" and "−", falls off rapidly as the distance between the charges increases.

In the absence of water, ionic forces are very strong. They are responsible for the strength of such minerals as marble and agate.

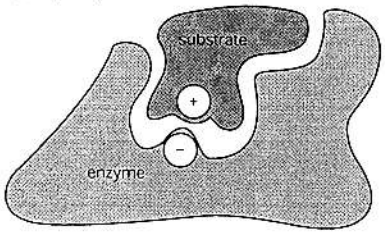

hand drawn
fig 2 109/2 07

a crystal of salt, NaCl

Similarly, other ions in solution can cluster around charged groups and further weaken ionic bonds.



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



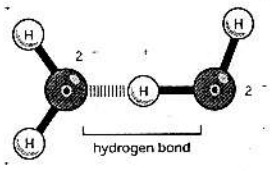
# Chemical Properties of Water - Part 1

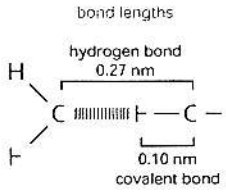


## HYDROGEN BONDS

Because they are polarized, two adjacent $H_2O$ molecules can form a linkage known as a hydrogen bond. Hydrogen bonds have only about 1/20 the strength of a covalent bond.

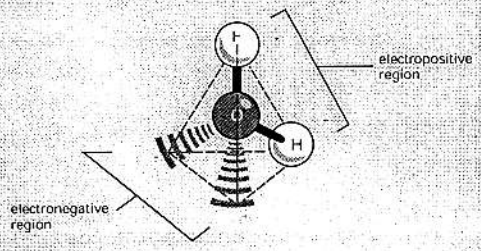
Hydrogen bonds are strongest when the three atoms lie in a straight line.




## WATER

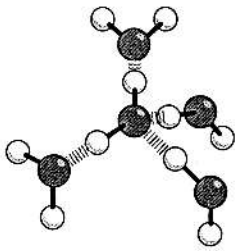
Two atoms, connected by a covalent bond, may exert different attractions for the electrons of the bond. In such cases the bond is polar, with one end slightly negatively charged ( $^-$) and the other slightly positively charged ( $^+$).




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

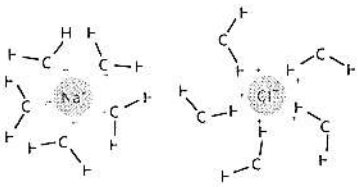
Molecules of water join together transiently in a hydrogen-bonded lattice. Even at 37°C, 15% of the water molecules are joined to four others in a short-lived assembly known as a "flickering cluster."



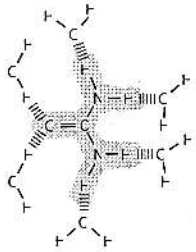
The cohesive nature of water is responsible for many of its unusual properties, such as high surface tension, specific heat, and heat of vaporization.

## 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.



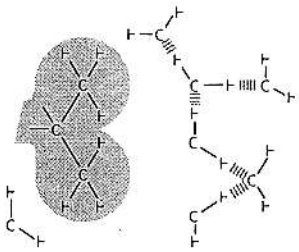
Ionic substances such as sodium chloride dissolve because water molecules are attracted to the positive ($Na^+$) or negative ($Cl^-$) charge of each ion.



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 non-polar 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.

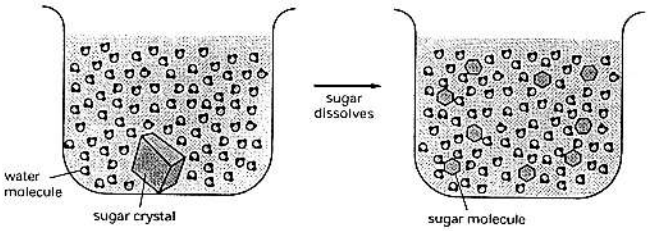


# Chemical Properties of Water - Part 2



## WATER AS A SOLVENT

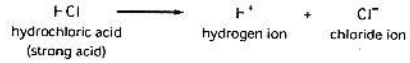
Many substances, such as household sugar, dissolve in water. That is, their molecules separate from each other, each becoming surrounded by water molecules.



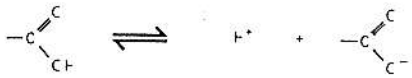

When a substance dissolves in a liquid, the mixture is termed a solution. The dissolved substance (in this case sugar) is the solute, and the liquid that does the dissolving (in this case water) is the solvent. Water is an excellent solvent for many substances because of its polar bonds.

## ACIDS

Substances that release hydrogen ions into solution are called acids.



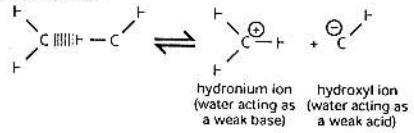

Many of the acids important in the cell are only partially dissociated, and they are therefore weak acids—for example, the carboxyl group (−COOH), which dissociates to give a hydrogen ion in solution




Note that this is a reversible reaction.

## HYDROGEN ION EXCHANGE

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




often written as: $H_2O \rightleftharpoons H^+ + OH^-$

hydrogen ion — hydroxyl ion

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).

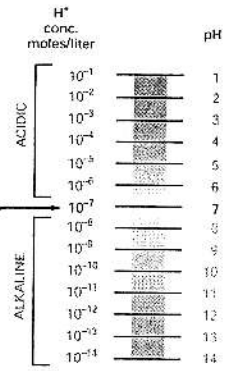
## pH

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

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

For pure water

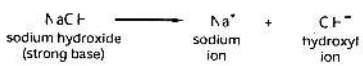
$[H^+] = 10^{-7}$ moles/liter



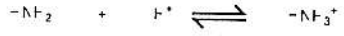

## BASES

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 $H^+$ ions indirectly, by making $OH^-$ ions that then combine directly with $H^+$ ions to make $H_2O$.

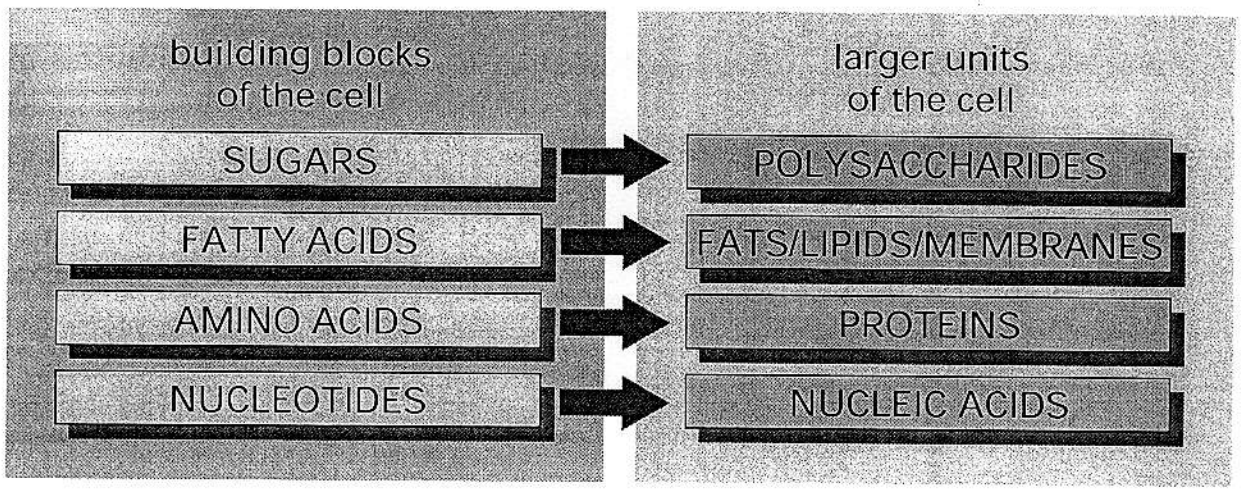



Many bases found in cells are partially dissociated and are termed weak bases. This is true of compounds that contain an amino group ($-NH_2$), which has a weak tendency to reversibly accept an $H^+$ ion from water, increasing the quantity of free $OH^-$ ions.



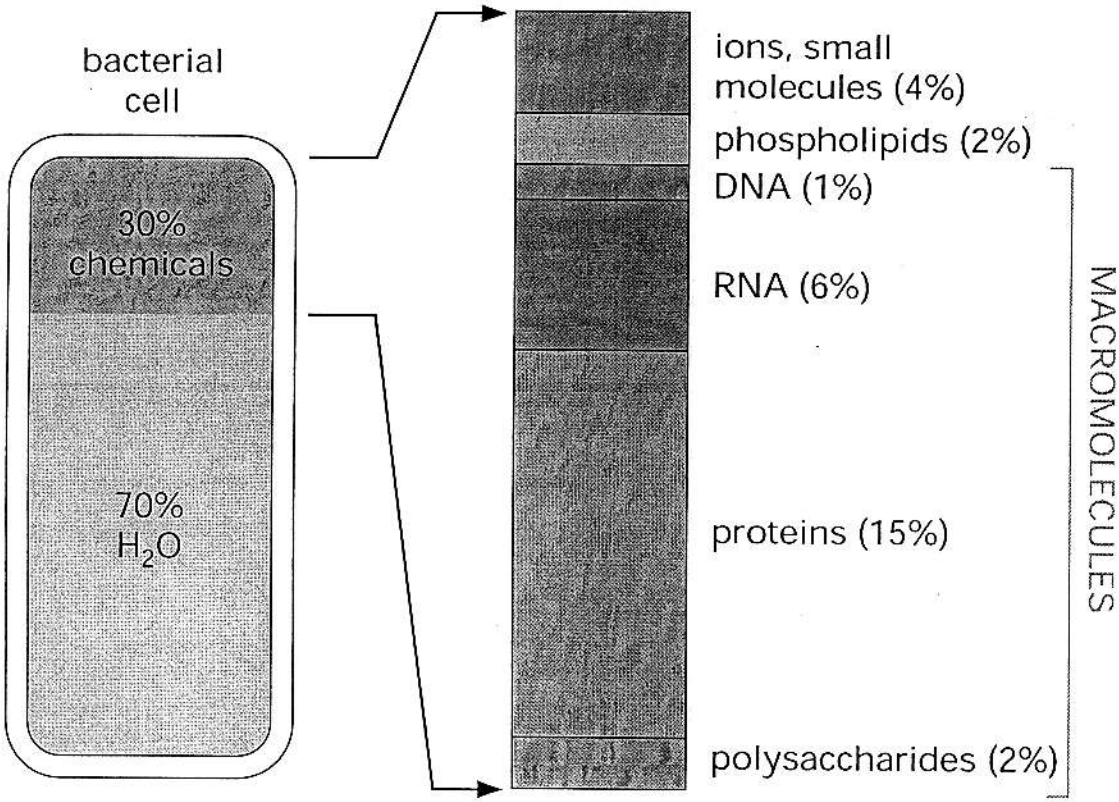
## Families of Small Organic Molecules





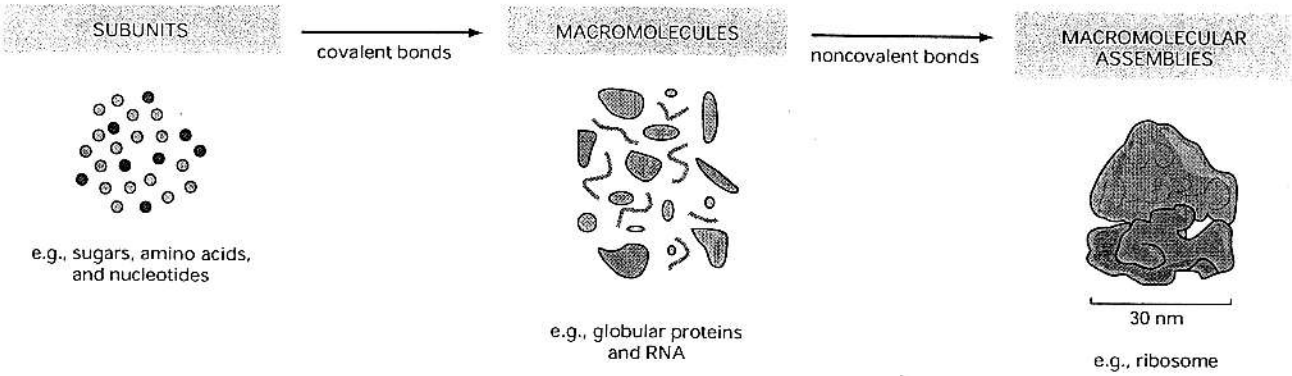
## Macromolecules in Cells





## Molecules Drawn to Scale



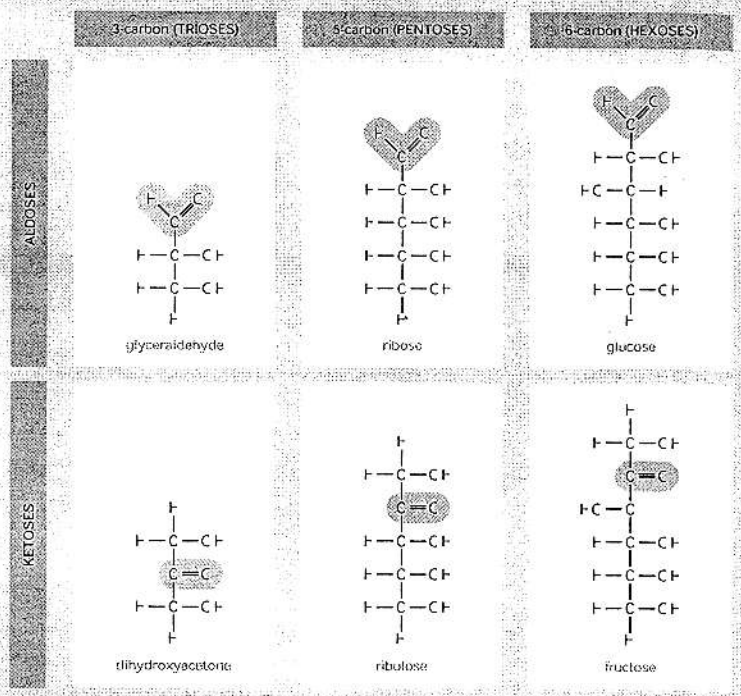


# Outline of Sugar Types Found in Cells - Part 1



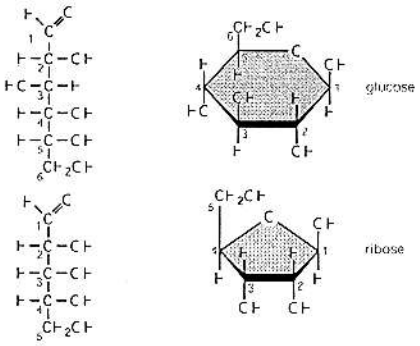
## MONOSACCHARIDES

Monosaccharides usually have the general formula $(CH_2O)_n$, where $n$ can be 3, 4, 5, 6, 7, or 8, and have two or more hydroxyl groups. They either contain an aldehyde group ($-C\overset{O}{<}_{H}$) and are called aldoses or a ketone group ($>C=O$) and are called ketoses.




## RING FORMATION

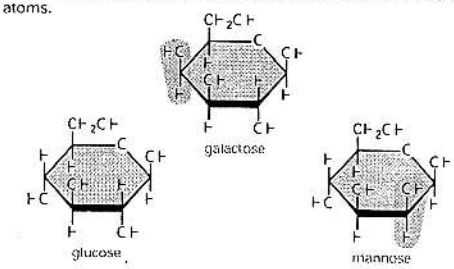
In aqueous solution, the aldehyde or ketone group of a sugar molecule tends to react with a hydroxyl group of the same molecule, thereby closing the molecule into a ring.




Note that each carbon atom has a number.

## 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 ($C_6H_{12}O_6$) but differ in the arrangement of groups around one or two carbon atoms.



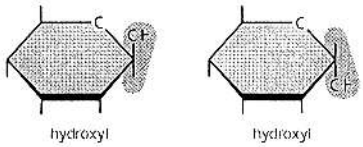

These small differences make only minor changes in the chemical properties of the sugars. But they are recognized by enzymes and other proteins and therefore can have important biological effects.

# Outline of Sugar Types Found in Cells - Part 2



## AND LINKS

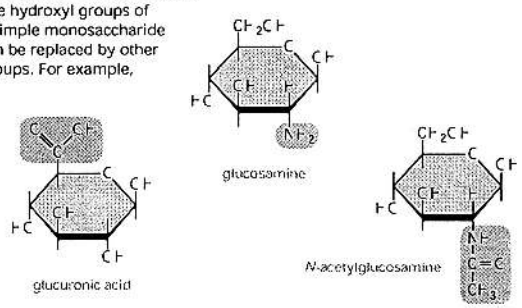
The hydroxyl group on the carbon that carries the aldehyde or ketone can rapidly change from one position to the other. These two positions are called and .




As soon as one sugar is linked to another, the or form is frozen.

## SUGAR DERIVATIVES

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

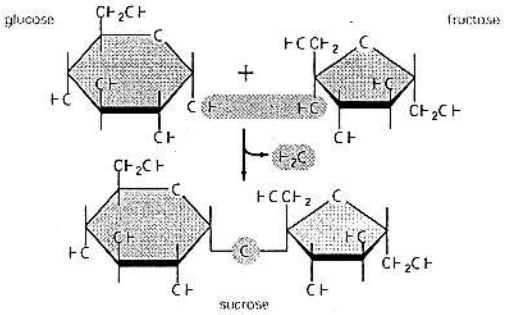



## DISACCHARIDES

The carbon that carries the aldehyde or the ketone can react with any hydroxyl group on a second sugar molecule to form a disaccharide. Three common disaccharides are

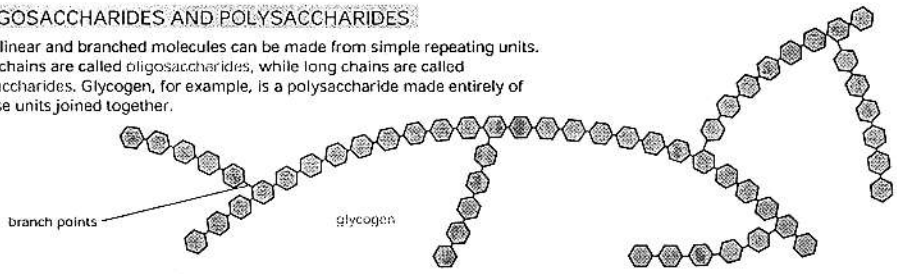
maltose (glucose + glucose)
lactose (galactose + glucose)
sucrose (glucose + fructose)

The reaction forming sucrose is shown here.



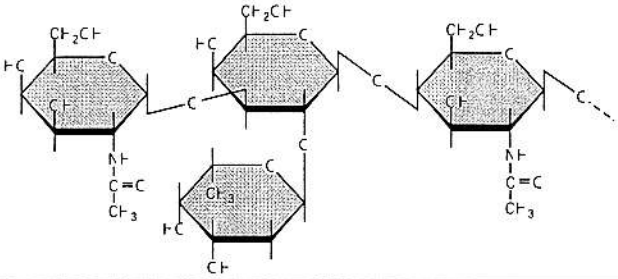

## OLIGOSACCHARIDES AND POLYSACCHARIDES

Large linear and branched molecules can be made from simple repeating units. 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.

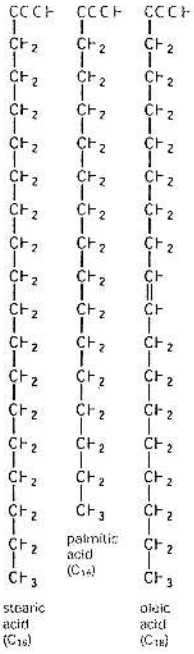


# Fatty Acids and Other Lipids - Part 1

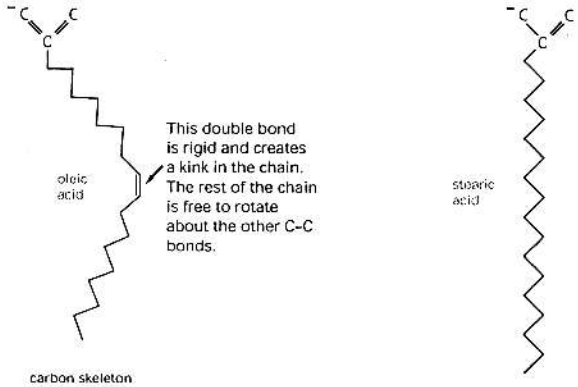


## COMMON FATTY ACIDS

These are carboxylic acids with long hydrocarbon tails.




Hundreds of different kinds of fatty acids exist. Some have one or more double bonds in their hydrocarbon tail and are said to be unsaturated. Fatty acids with no double bonds are saturated.

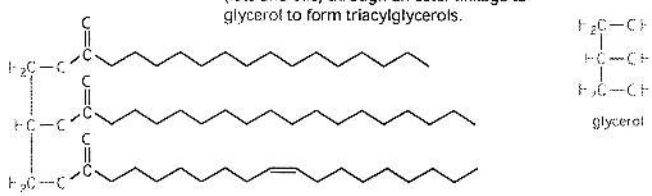



space-filling model carbon skeleton
UNSATURATED

SATURATED

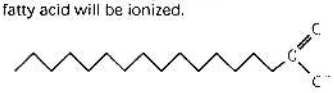
## TRIACYLGLYCEROLS

Fatty acids are stored as an energy reserve (fats and oils) through an ester linkage to glycerol to form triacylglycerols.

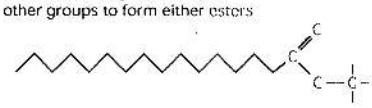



## CARBOXYL GROUP

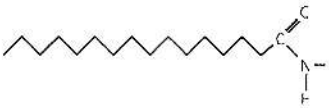
If free, the carboxyl group of a fatty acid will be ionized.



But more usually it is linked to other groups to form either esters

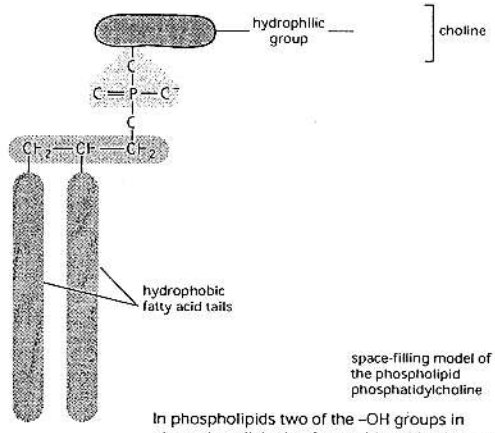


or amides.



## PHOSPHOLIPIDS

Phospholipids are the major constituents of cell membranes.




space-filling model of the phospholipid phosphatidylcholine

general structure of a phospholipid

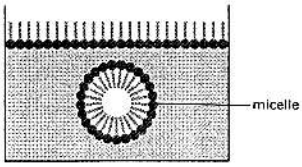
In phospholipids two of the –OH groups in glycerol are linked to fatty acids, while the third –OH group is linked to phosphoric acid. The phosphate is further linked to one of a variety of small polar groups (alcohols).

# Fatty Acids and Other Lipids - Part 2



## LIPID AGGREGATES

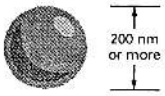
Fatty acids have a hydrophilic head and a hydrophobic tail.



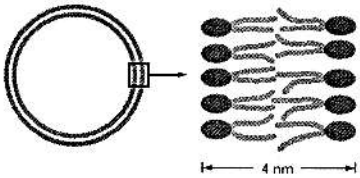

In water they can form a surface film or form small micelles.

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

Triglycerides form large spherical fat droplets in the cell cytoplasm.

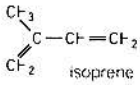



Phospholipids and glycolipids form self-sealing lipid bilayers that are the basis for all cellular membranes.



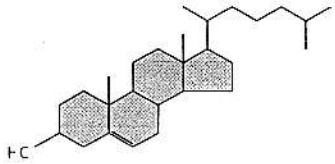

## OTHER LIPIDS

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.

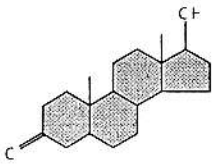



## STEROIDS

Steroids have a common multiple-ring structure.



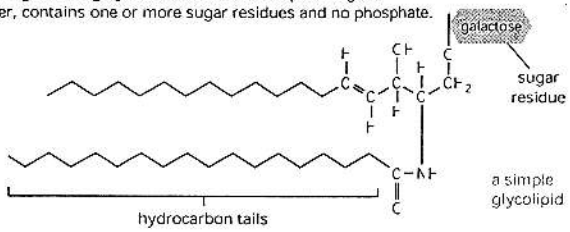
cholesterol—found in many membranes



testosterone—male steroid hormone

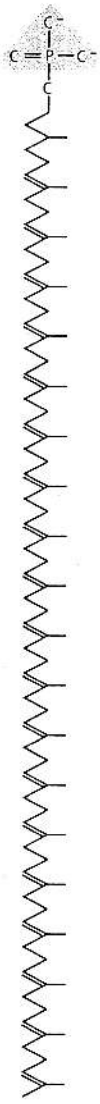
## GLYCOLIPIDS

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 sugar residues 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

# Amino Acids Found in Proteins - Part 1



## FAMILIES OF AMINO ACIDS

The common amino acids are grouped according to whether their side chains are

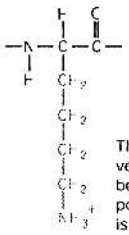
- acidic
- basic
- uncharged polar
- nonpolar

These 20 amino acids are given both three-letter and one-letter abbreviations.

Thus: alanine = Ala = A

## BASIC SIDE CHAINS

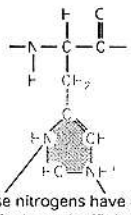
lysine (Lys, or K)



This group is very basic because its positive charge is stabilized by resonance.

arginine (Arg, or R)

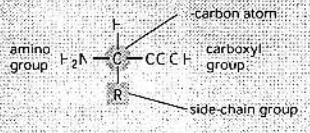
histidine (His, or H)



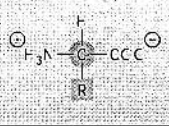
These nitrogens have a relatively weak affinity for an $H^+$ and are only partly positive at neutral pH.

## THE AMINO ACID

The general formula of an amino acid is

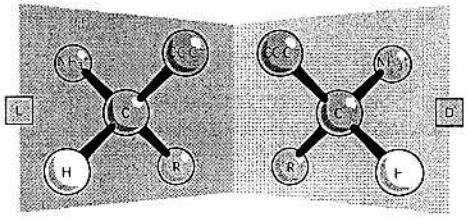



R is commonly one of 20 different side chains. At pH 7 both the amino and carboxyl groups are ionized.



## OPTICAL ISOMERS

The -carbon atom is asymmetric, which allows for two mirror image (or stereo-) isomers, L and D.

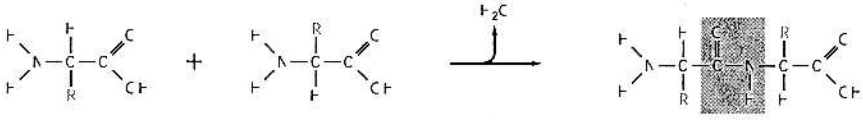



Proteins consist exclusively of L-amino acids.

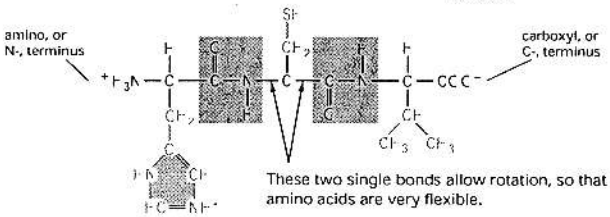
## PEPTIDE BONDS

Amino acids are commonly joined together by an amide linkage, called a peptide bond.

Peptide bond: The four atoms in each *gray box* form a rigid planar unit. There is no rotation around the C–N bond.



Proteins are long polymers of amino acids linked by peptide bonds, and they are always written with the N-terminus toward the left. The sequence of this tripeptide is histidine-cysteine-valine.



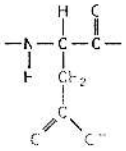

These two single bonds allow rotation, so that long chains of amino acids are very flexible.

# Amino Acids Found in Proteins - Part 2

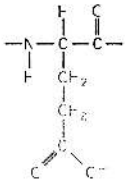


## ACIDIC SIDE CHAINS

aspartic acid
(Asp, or D)

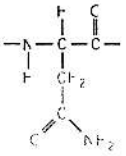


glutamic acid
(Glu, or E)

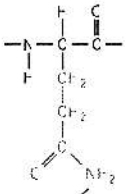


## UNCHARGED POLAR SIDE CHAINS

asparagine
(Asn, or N)

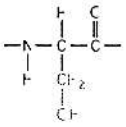


glutamine
(Gln, or Q)

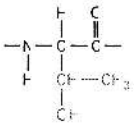


Although the amide N is not charged at neutral pH, it is polar.

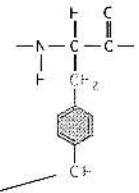
serine
(Ser, or S)



threonine
(Thr, or T)



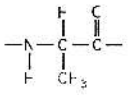
tyrosine
(Tyr, or Y)



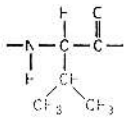
The -OH group is polar.

## NONPOLAR SIDE CHAINS

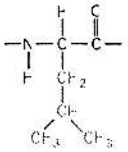
alanine
(Ala, or A)



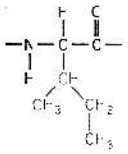
valine
(Val, or V)



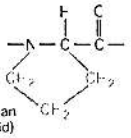
leucine
(Leu, or L)



isoleucine
(Ile, or I)

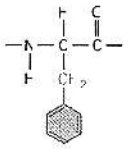


proline
(Pro, or P)

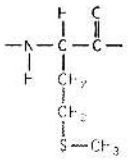


(actually an imino acid)

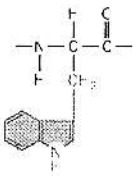
phenylalanine
(Phe, or F)



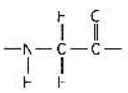
methionine
(Met, or M)



tryptophan
(Trp, or W)



glycine
(Gly, or G)



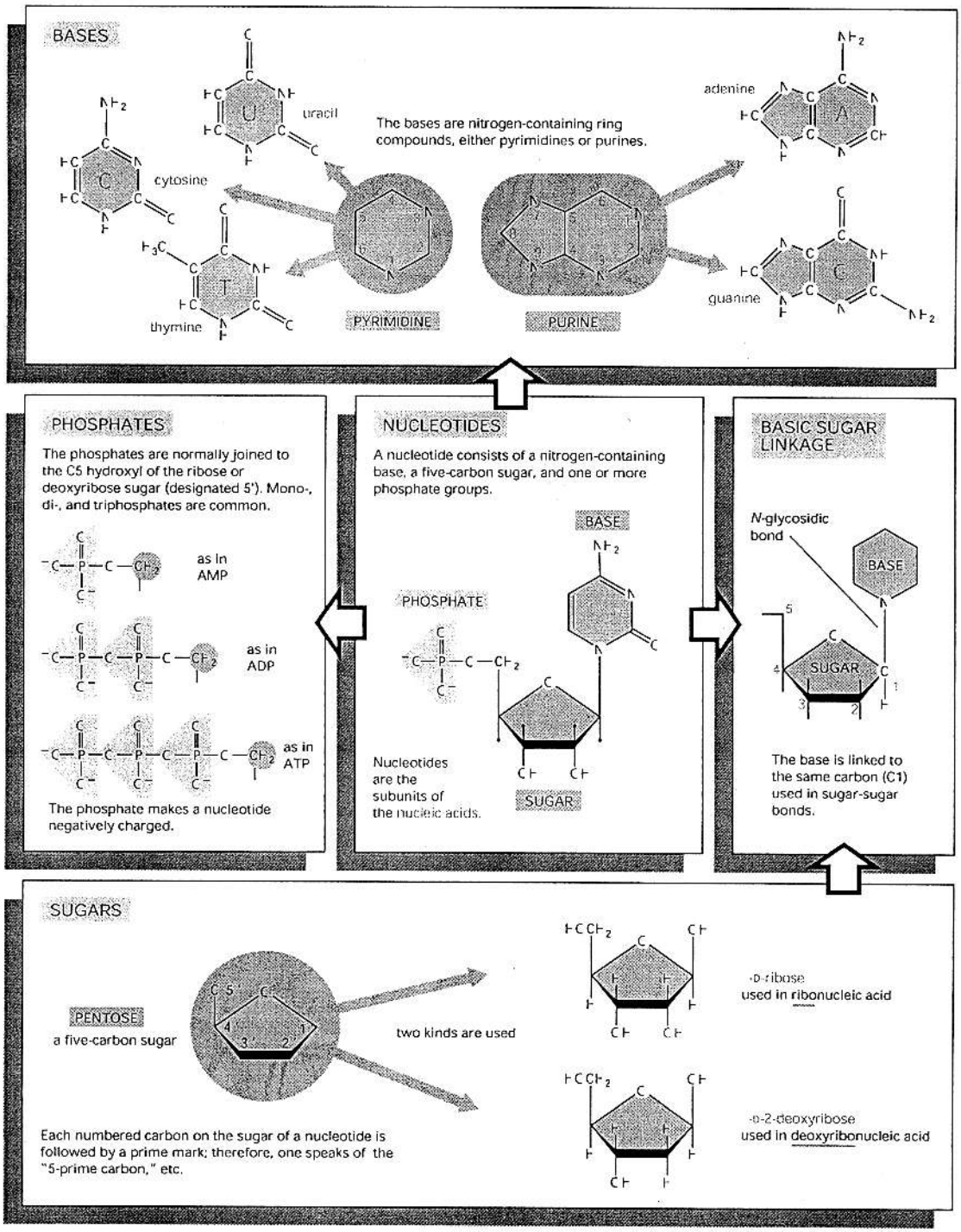
cysteine
(Cys, or C)

Disulfide bonds can form between two cysteine side chains in proteins.

$$-\!-CH_2\!-\!S-S-CH_2\!-\!-$$

# Survey of Nucleotides - Part 1





# Survey of Nucleotides - Part 2



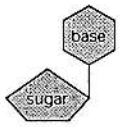
## NOMENCLATURE

The names can be confusing, but the abbreviations are clear.

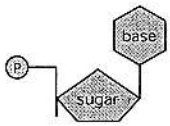
| BASE | NUCLEOSIDE | ABBR. |
|---|---|---|
| adenine | adenosine | A |
| guanine | guanosine | G |
| cytosine | cytidine | C |
| uracil | uridine | U |
| thymine | thymidine | T |

Nucleotides are abbreviated by three capital letters. Some examples follow:

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



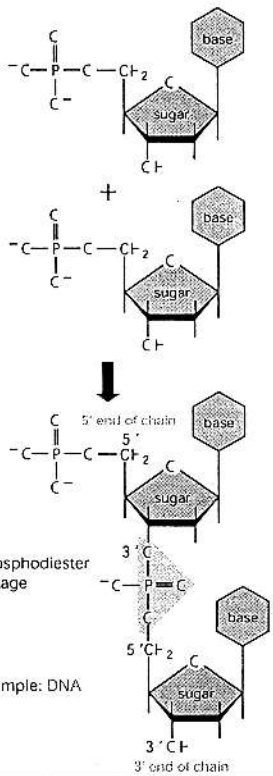

BASE + SUGAR = NUCLEOSIDE




BASE + SUGAR + PHOSPHATE = NUCLEOTIDE

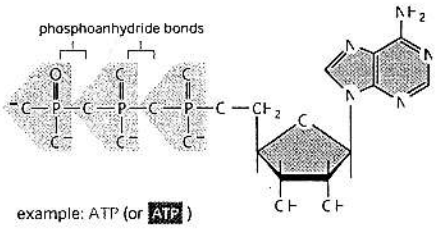
## NUCLEIC ACIDS

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.



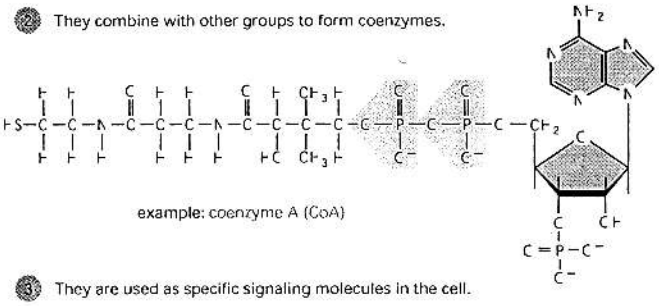

## NUCLEOTIDES HAVE MANY OTHER FUNCTIONS

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




example: ATP (or ATP)

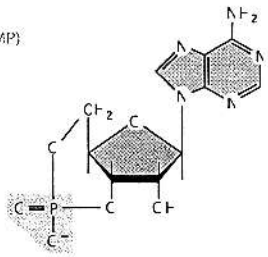
2. They combine with other groups to form coenzymes.



example: coenzyme A (CoA)

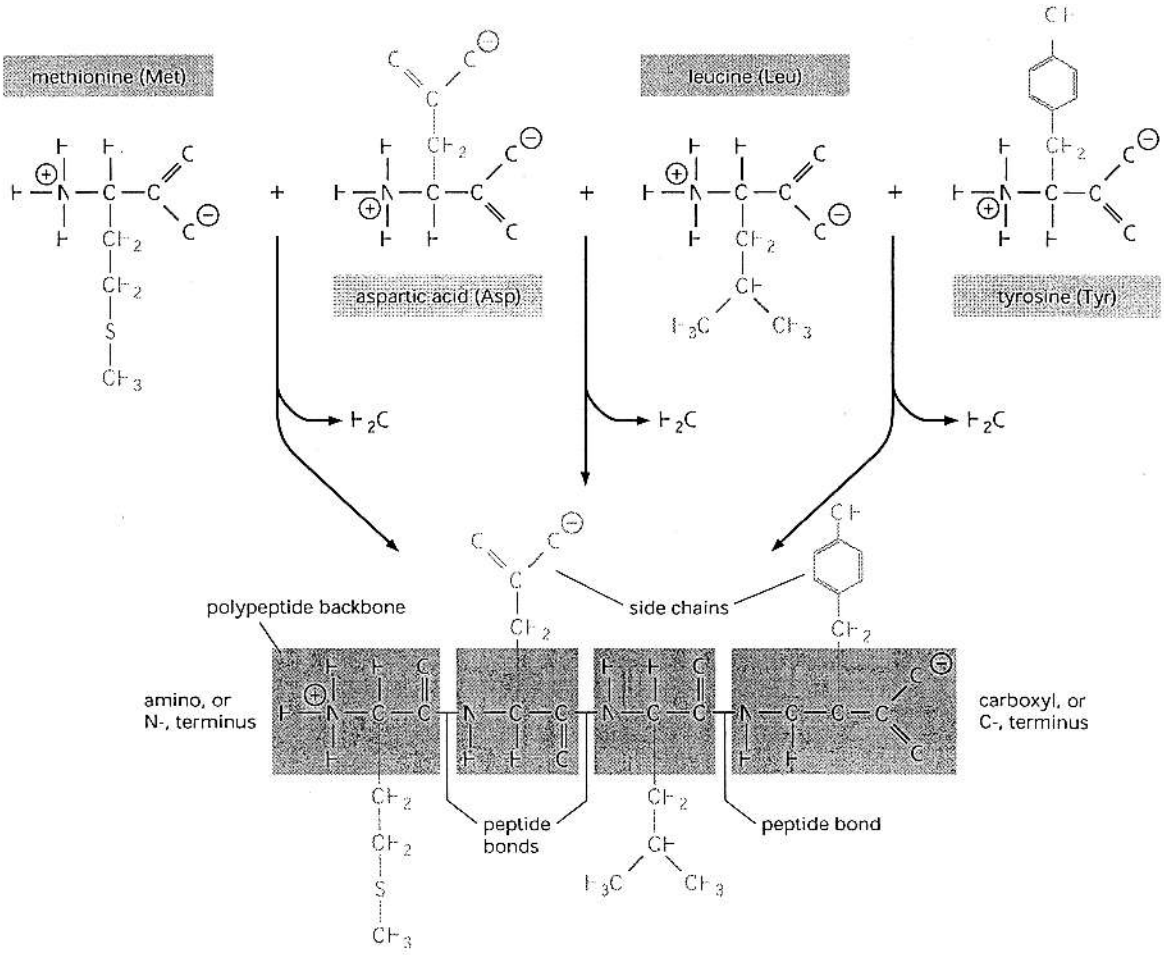
3. They are used as specific signaling molecules in the cell.

example: cyclic AMP (cAMP)



# Protein Structure



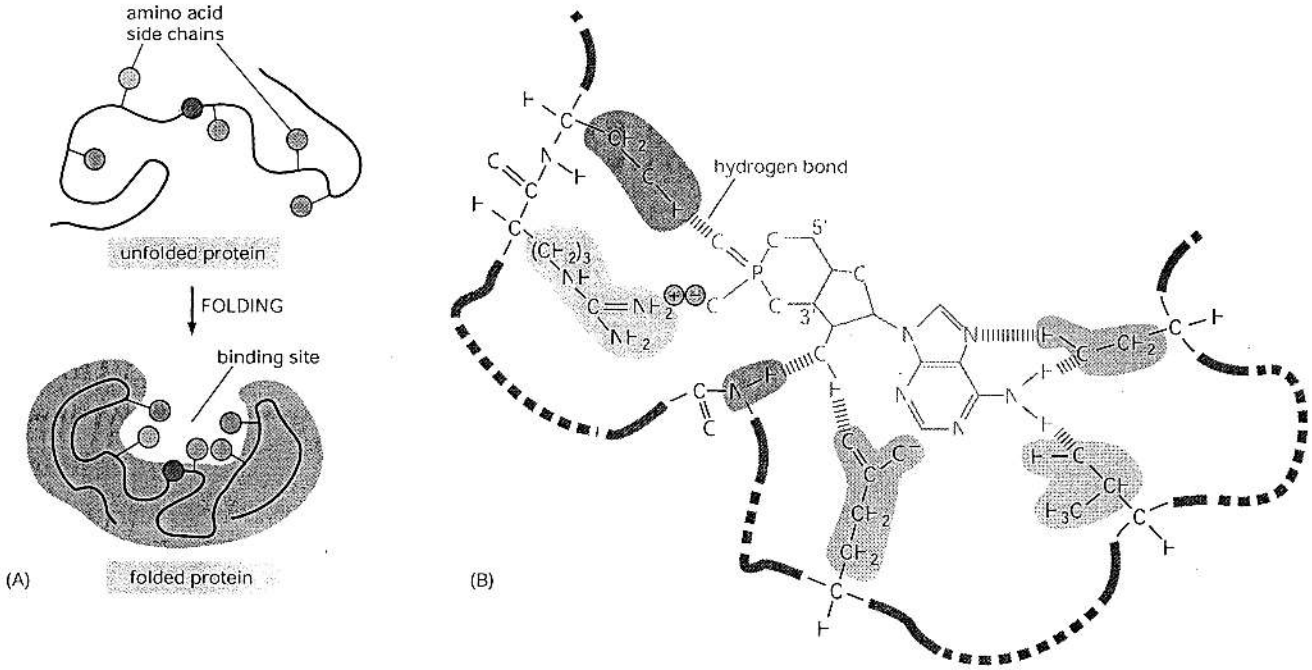



SCHEMATIC

SEQUENCE Met — Asp — Leu — Tyr

# Binding of a Protein





# Mammalian Differentiated Cell Types, Part1



## CELL TYPES

There are over 200 types of cells in the human body. These are assembled into a variety of types of tissue such as

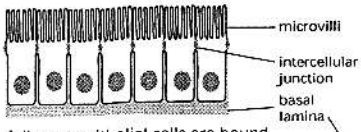
- epithelia
- connective tissue
- muscle
- nervous tissue

Most tissues contain a mixture of cell types.

## EPITHELIA

Epithelial cells form coherent cell sheets called epithelia, which line the inner and outer surfaces of the body. There are many specialized types of epithelia.

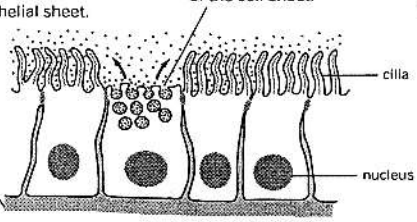
Absorptive cells have numerous hairlike projections called microvilli on their free surface to increase the area for absorption.




Adjacent epithelial cells are bound together by cell junctions that give the sheet mechanical strength and also make it impermeable to small molecules. The sheet rests on a basal lamina.

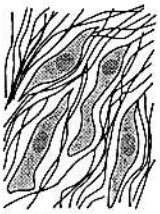
Ciliated cells have cilia on their free surface that beat in synchrony to move substances (such as mucus) over the epithelial sheet.

Secretory cells are found in most epithelial layers. These specialized cells secrete substances onto the surface of the cell sheet.



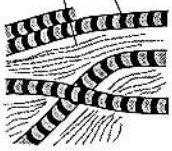

## CONNECTIVE TISSUE

The spaces between organs and tissues in the body are filled with connective tissue made principally of a network of tough protein fibers embedded in a polysaccharide gel. This extracellular matrix is secreted mainly by fibroblasts.

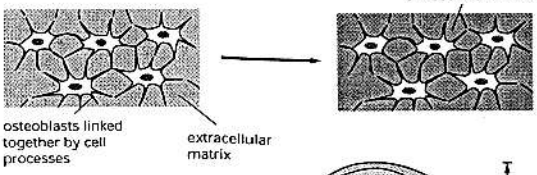


fibroblasts in loose connective tissue

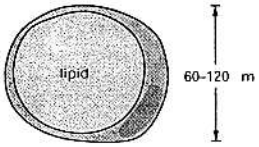
Two main types of extracellular protein fiber are collagen and elastin.



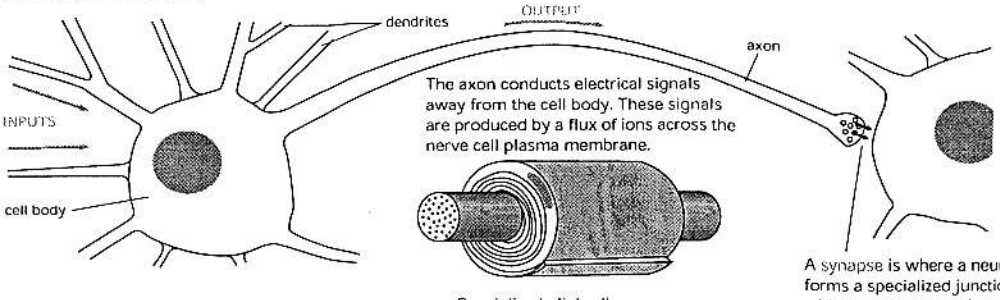
Bone is made by cells called osteoblasts. These secrete an extracellular matrix in which crystals of calcium phosphate are later deposited.




Fat cells (or adipose cells), among the largest cells in the body, are responsible for the production and storage of fat. The nucleus and cytoplasm are squeezed by a large lipid droplet.




## NERVOUS TISSUE




The axon conducts electrical signals away from the cell body. These signals are produced by a flux of ions across the nerve cell plasma membrane.

Nerve cells, or neurons, are specialized for communication. The brain and spinal cord, for example, are composed of a network of neurons among supporting glial cells.

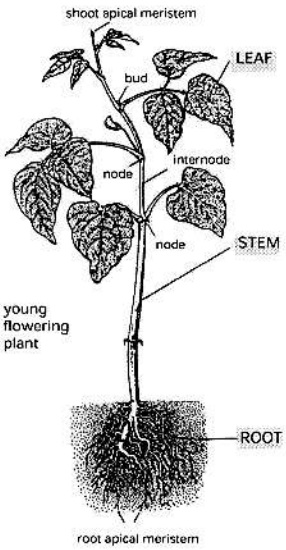
Specialized glial cells wrap around an axon to form a multilayered membrane sheath.

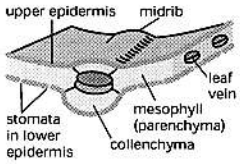
A synapse is where a neuron forms a specialized junction with another neuron (or with a muscle cell). At synapses, signals pass from one neuron to another (or from a neuron to a muscle cell).

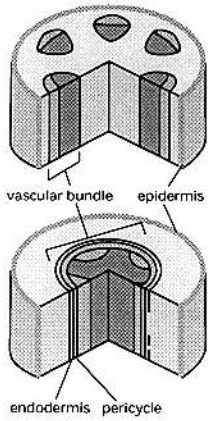
# Plant Cells and Tissues, Part 1



## THE PLANT




The young flowering plant shown on the *left* is constructed from three main types of organs: leaves, stems, and roots. Each plant organ in turn is made from three tissue systems: ground (▭), dermal (▭), and vascular (▭).

All three tissue systems derive ultimately from the cell proliferative activity of the shoot or root apical meristems, and each contains a relatively small number of specialized cell types. These three common tissue systems, and the cells that comprise them, are described in this panel.

### THE THREE TISSUE SYSTEMS

Cell division, growth, and differentiation give rise to tissue systems with specialized functions.

DERMAL TISSUE: This is the plant's protective outer covering in contact with the environment. It facilitates water and ion uptake in roots and regulates gas exchange in leaves and stems.

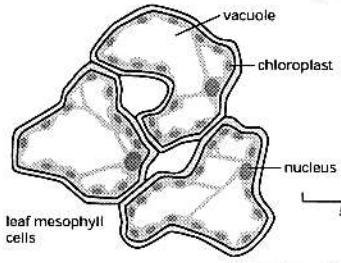
VASCULAR TISSUE: Together the phloem and the xylem form a continuous vascular system throughout the plant. This tissue conducts water and solutes between organs and also provides mechanical support.

GROUND TISSUE: This packing and supportive tissue accounts for much of the bulk of the young plant. It also functions in food manufacture and storage.

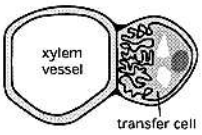
## GROUND TISSUE

The ground tissue system contains three main cell types called parenchyma, collenchyma, and sclerenchyma.

Parenchyma cells are found in all plant tissue systems. They are living cells, generally capable of further division, and have a thin primary cell wall. These cells have a variety of functions. The apical and lateral meristematic cells of shoots and roots provide the new cells required for growth. Food production and storage occur in the photosynthetic cells of the leaf and stem (called mesophyll cells); storage parenchyma cells form the bulk of most fruits and vegetables. Because of their proliferative capacity, parenchyma cells also serve as sources of new cells for wound healing and regeneration.

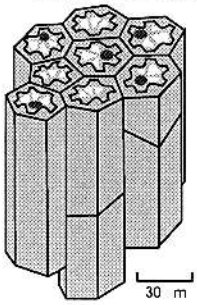


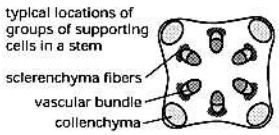




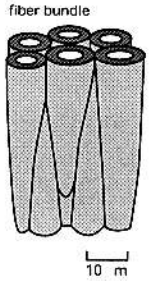

A transfer cell, a specialized form of parenchyma cell, is readily identified by elaborate ingrowths of the primary cell wall. The increase in the area of the plasma membrane beneath these walls facilitates the rapid transport of solutes to and from cells of the vascular system.

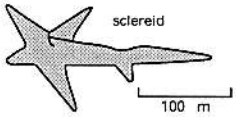
Collenchyma are living cells similar to parenchyma cells except that they have much thicker cell walls and are usually elongated and packed into long ropelike fibers. They are capable of stretching and provide mechanical support in the ground tissue system of the elongating regions of the plant. Collenchyma cells are especially common in subepidermal regions of stems.




Sclerenchyma, like collenchyma, have strengthening and supporting functions. However, they are usually dead cells with thick, lignified secondary cell walls that prevent them from stretching as the plant grows. Two common types are fibers, which often form long bundles, and sclereids, which are shorter branched cells found in seed coats and fruit.



# Simplified Diagram of Cellular Metabolism