12

UNUSUAL PROPERTIES OF WATER

Modern chemistry and physics have disclosed that water is vastly different from almost any other small molecule. Its unusual properties are a direct result of the polar nature of the water molecule explained in Plate 11.

Color title A and the related illustration.

Water is not only a *good solvent,* it is the best. It dissolves more different substances than any other solvent known. This is because so many other molecules are ionic or polar, and their electrical charges make them attracted to the water molecules, causing them to stay in solution. Thus we find that water dissolves many kinds of salts and sugars, many proteins, such as gelatin, and a variety of hormones that dissolve in our blood (since blood is mostly water) and regulate various life processes. Even nonpolar molecules dissolve to some extent if they are small. Thus enough oxygen dissolves to allow fish and other aquatic animals to survive, and enough carbon dioxide dissolves to enable algae and many plants to live underwater.

Color title B and the related illustration.

A capillary is any tube of extremely small diameter, including the tiniest of our blood vessels. If a capillary tube is made of glass or any other substance that is polar, water will spontaneously climb up inside it without having to be pumped in any way. The smaller the tube, the higher the water climbs. The attraction is so great between the water molecules and the molecules of the tube that water will climb in defiance of the force of gravity. This is termed *capillary action.*

Color title C and the related illustration.

Water is also unusual in being able to absorb a lot of heat energy without having its temperature increase by very much. (A scientist would say it has a *high specific heat.*) An amount of heat that will raise the temperature of a container of water by 10 degrees will raise the temperature of an equal weight of alcohol by 20 degrees and an equal weight of iron by 94 degrees. Water molecules are held together so strongly by their hydrogen bonds that an amount of heat that will get other molecules moving much faster will not speed up water molecules much at all. This property of water helps to reduce temperature fluctuations in the animal or plant body, and it also makes for mild climates in the vicinity of large bodies of water.

Color titles D and E and the related illustrations.

Heat of vaporization is the amount of heat energy required to evaporate a given weight of a liquid. Water has a very *high heat of vaporization,* which means that it takes a lot of heat to evaporate just a little water. This keeps water in many more lakes and ponds during the summer than would be the case if water had a lower heat of vaporization. Heat of fusion is the heat energy that must be removed from a given weight of water in order to freeze it. Water's relatively *high heat of fusion* means that it takes much longer for lakes and streams to freeze in the winter, allowing living things more time to adjust to the change.

Color title F and the related illustration.

Hydrogen bonds hold water molecules together so tightly that the water's surface acts like a membrane. The insect known as the water strider is actually able to walk on that surface without breaking through.

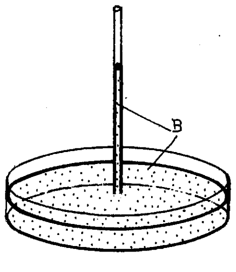
Color title G and the related illustration.

Almost everything contracts when it is cooled, and water is no exception, up to a point. That point is 3.8°C. When cooled below that temperature, water molecules slow down and start to arrange themselves into a crystal structure in which each water molecule is hydrogen-bonded to four other water molecules. This structure is completed when the water freezes. What is most unusual is that this crystal structure takes up more space than the same molecules did in the liquid state, so ice is less dense than water, and it floats. The water below is still at 3.8°C. Since ice is a good insulator, lakes and ponds can freeze over in the winter without freezing all the living things in the water below. If ice didn't float, lakes would freeze from the bottom up, and many of them would eventually freeze solid, killing all life in them.

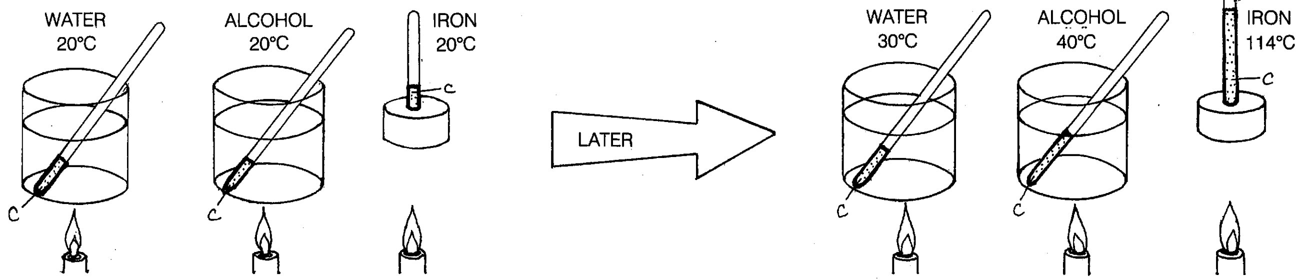
UNUSUAL PROPERTIES OF WATER.

GOOD SOLVENT$_{A}$

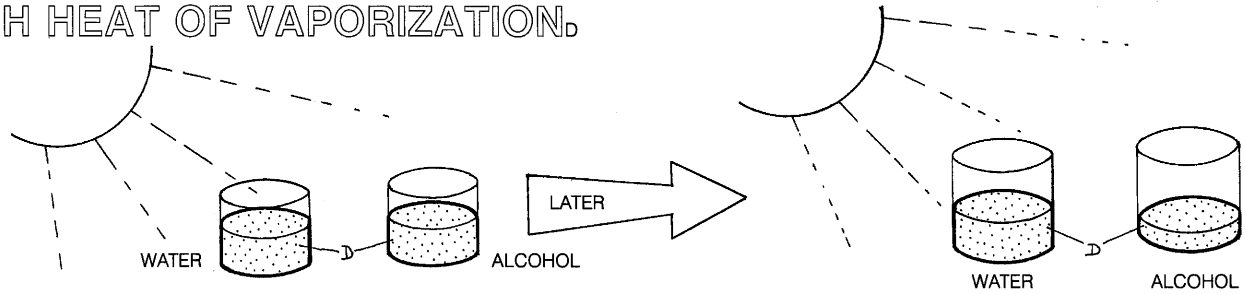
CAPILLARY ACTION$_{B}$



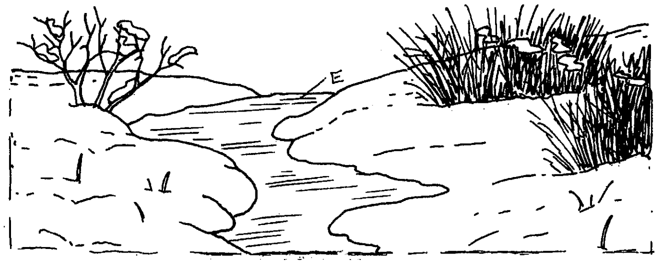
HIGH SPECIFIC HEAT$_{C}$



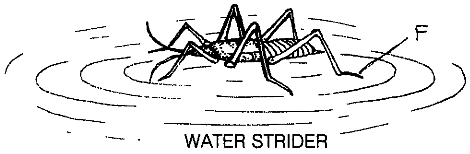
HIGH HEAT OF VAPORIZATION$_{D}$



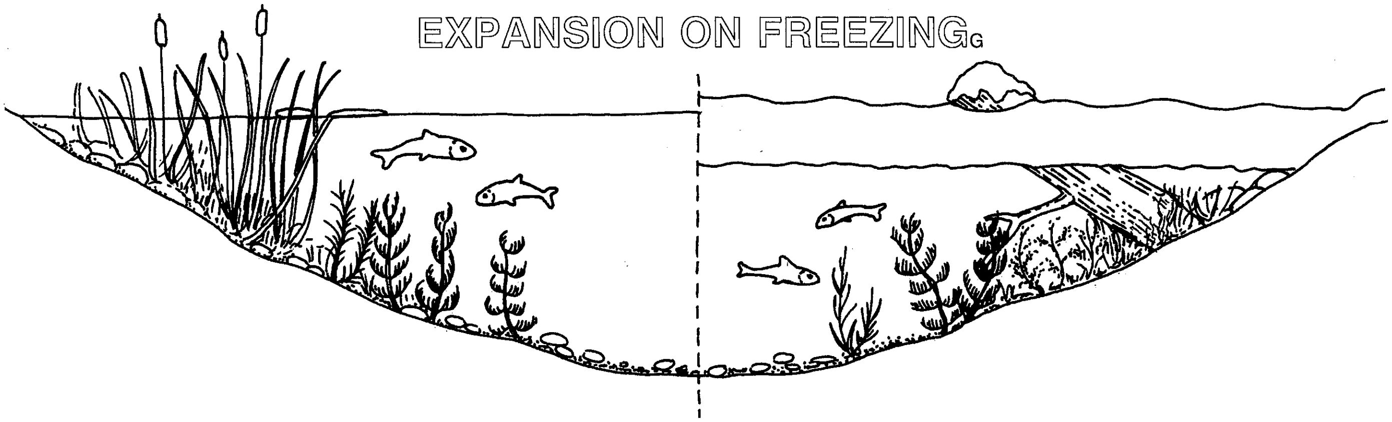
HIGH HEAT OF FUSION$_{E}$



HIGH SURFACE TENSION$_{F}$



EXPANSION ON FREEZING$_{G}$



13

ACIDS AND BASES

You saw in Plate 9 that some atoms can gain or lose electrons to form ions. That process is called ionization, and compounds formed in that way are called ionic compounds. When ionic compounds dissolve in water, their ions separate from one another in a process called dissociation (the opposite of association). One interesting feature of water and many other covalent compounds is that they, too, can dissociate into ions. Unlike ionic compounds, such as sodium chloride, they are not ionized before they dissociate; they accomplish ionization and dissociation simultaneously.

Color the heading Dissociation of Water, titles H_2O through H_3O^+, and the related structures.

When *water dissociates,* one of the hydrogen nuclei leaves its electron behind with the oxygen atom to become a *hydrogen ion,* while the oxygen and the other hydrogen atom become a *hydroxide ion.* Since the hydrogen ion has no electron to neutralize the positive charge on its proton, it has a full unit of positive charge and is symbolized as H^+. The hydroxide ion retains the electron left behind by the departed hydrogen and therefore has one more electron than it has protons, so it has a full unit of negative charge and is symbolized as OH^-. The hydrogen ion (really just a proton except in the rare isotopes of hydrogen) does not wander long by itself before it attaches to the oxygen atom of a second, un-ionized water molecule to form a *hydronium ion* (H_3O^+).

In any sample of water, very few of the molecules are dissociated at any one time: in fact, only about one in 550 million. There is, however, a constant change; as one hydrogen ion reattaches to a hydroxide ion to form a water molecule, another water molecule dissociates to replace the hydrogen ion and hydroxide ion in solution.

Color the heading Hydrochloric Acid, title Cl^-, and the related structures.

Certain molecules, ionic and covalent, dissociate in such a way that they release a hydrogen ion without releasing a hydroxide ion. These substances are called acids. Since a hydrogen ion is really just a single proton in most cases, the chemist's definition of an acid is a "proton donor." If very many protons (hydrogen ions) are "donated," the effect can be very profound, burning your skin, dissolving a metal, and the like. The acid illustrated is hydrochloric acid. Pure hydrochloric acid is a gas, but it dissolves easily in water to produce a solution of hydrogen ion and *chloride ion.* Since nearly all of it is dissociated in water, it is called a strong acid. (Acids that do not dissociate completely are called weak acids.)

Color the heading Sodium Hydroxide, title Na^+, and the related structures.

The opposite of an acid is a base, better known in everyday language as an alkali. A typical strong base is sodium hydroxide, the principal component of lye, which dissociates in water to form *sodium ion* and hydroxide ion. A base is defined as a "proton acceptor." The most common bases produce hydroxide ion when they dissociate, and it is the hydroxide ion that accepts the proton. (A strong base can give your skin a much worse burn than an acid.)

Color the heading Neutralization, title B, and the related structures.

When a base and an acid are mixed, the hydroxide ion from the base combines with the hydrogen ion from the acid to form water. This process is called *neutralization.*

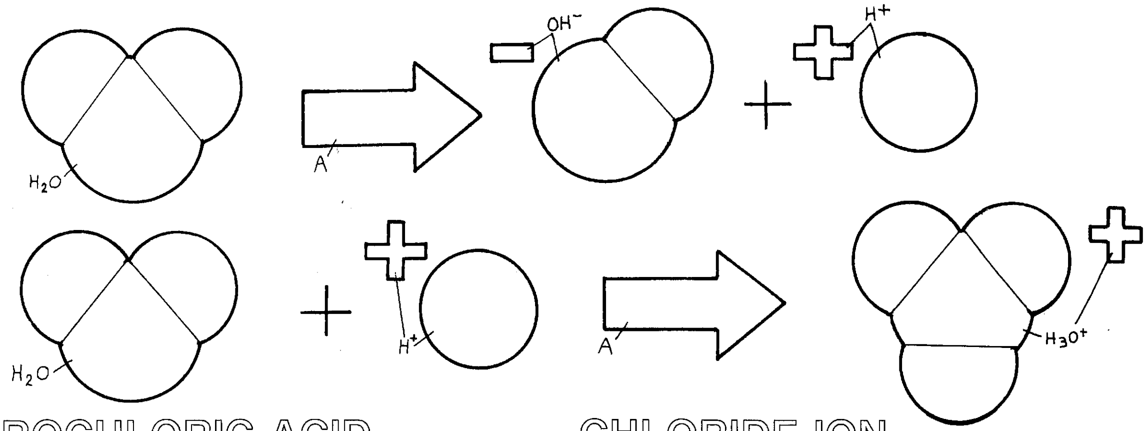
Color the heading pH Scale, titles H^+ and OH^-, and the related portions of the bar representing the pH scale.

The quantities of acids and bases found in living organisms are extremely small in comparison with the solutions normally used in chemistry laboratories. As a result, biologists have adopted the pH scale. The pH scale ranges from 0 at the acid end to 14 at the basic end. These two extremes (pH 0 and pH 14) are only mildly acidic and mildly basic by comparison with many other acids and bases, but they are strong enough to be lethal to a living thing. Each change of one pH unit indicates a tenfold increase or decrease in *hydrogen ion concentration* and the opposite tenfold change in *hydroxide ion concentration.* Pure water has a pH of 7, which means it has equal (though extremely small) concentrations of hydrogen ion and hydroxide ion (10^{-7} molar, if you are a chemist). A solution with a pH of 6 has ten times the hydrogen ion concentration of a pH 7 solution and only one-tenth the hydroxide ion concentration; it is therefore slightly acidic. Most fluids in living things have a pH not too far from 7, although stomach acid can get to pH 1.

ACIDS AND BASES.

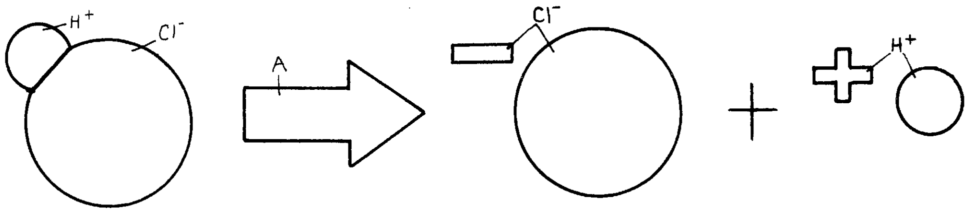
DISSOCIATION OF WATER★

WATER$_{H_2O}$ DISSOCIATION$_A$ HYDROXIDE ION$_{OH^-}$
HYDROGEN ION$_{H^+}$ HYDRONIUM ION$_{H_3O^+}$



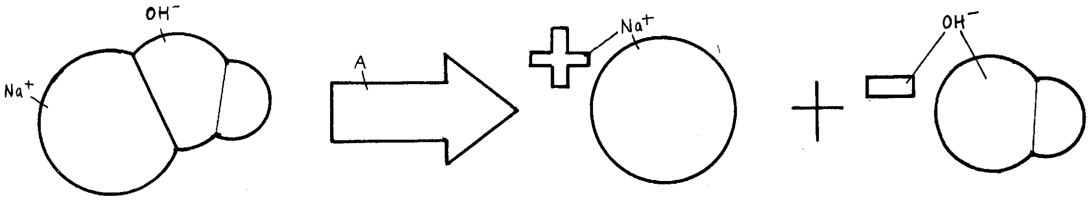
HYDROCHLORIC ACID★

CHLORIDE ION$_{Cl^-}$



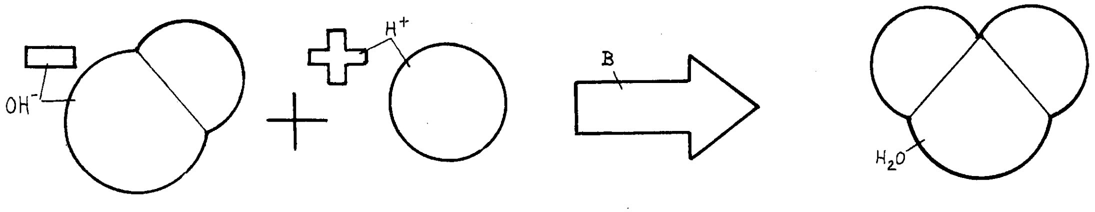
SODIUM HYDROXIDE★

SODIUM ION$_{Na^+}$



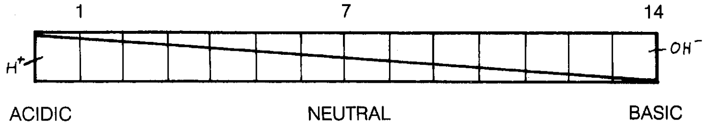
NEUTRALIZATION★

NEUTRALIZATION$_B$



pH SCALE★

HYDROGEN ION CONC.$_{H^+}$ HYDROXIDE ION CONC.$_{OH^-}$



14
CARBOHYDRATES I

The processes of life are primarily the result of the chemistry of compounds of carbon. In fact, all except a very few simple compounds of carbon are called "organic" compounds. Because of carbon's tendency to form four covalent bonds in four different directions, as we saw with methane in Plate 10, carbon can form an unbelievably large number of different compounds of high complexity. This plate introduces you to one major category of such compounds, the carbohydrates (hydrates of carbon).

Color the headings L-Glycerose Isomer and D-Glycerose Isomer, title C+H+O, and its representation.

"Hydrate" means something combined with water, and carbohydrates have approximately two hydrogen atoms and one oxygen atom (amounting to one water molecule) for every carbon atom. The general formula for carbohydrates is $(CH_2O)_n$, where n can be almost any number. For glycerose, illustrated here, n is 3; multiplying everything within the parentheses by 3, we get an empirical formula of $C_3H_6O_3$.

Color titles A through O, the heading Shared Electrons, titles B and B_1, and all remaining structures. Again it is recommended that you use the standard colors: black for carbon, white or yellow for hydrogen, and red for oxygen. You may wish to use shades of gray for B and B^1. As you color, keep in mind that the lines and sticks represent pairs of shared electrons, which we call covalent bonds. The term "bond" refers only to the attractive force between the two atoms, not to any actual object or structure.

The simplest carbohydrate is glycerose. The ending "-ose" indicates that it is a sugar. It is an example of a class of molecules called monosaccharides ("single sugars"). Notice that glycerose has only three *carbon* atoms. Other monosaccharides have from four to nine carbon atoms. The most common monosaccharides have five or six.

Sometimes glycerose is called glyceraldehyde because of the arrangement of atoms around carbon atom number 1 (the uppermost one). Any carbon atom sharing *one pair of electrons* with a *hydrogen atom* and *two pairs of electrons* with an *oxygen atom* constitutes what chemists call an *aldehyde group.* Several other important sugars are also aldehydes. This is the first compound we have discussed in which two atoms share two pairs of electrons instead of only one pair. This arrangement is called a "double bond" and is not uncommon.

The most common way of representing the three-dimensional structure of carbon compounds on a flat sheet of paper is the Fischer projection formula, named after Emil Fischer, a great German chemist of the nineteenth century who first proposed this method. The three-dimensional structure is arranged so that the carbon atoms are in a vertical line (although the upper and lower carbon atoms are farther away from the viewer than the middle one), and the atoms to the left and right of the center carbon atom project toward the viewer. The atoms are "projected" onto the paper, much as you might do with an overhead or opaque projector or with just a bright light to cast shadows. The ball-and-stick and space-filling models are arranged this way, and a projection of them onto a flat surface will give the projection formula illustrated here. If this is difficult for you to visualize, you can make your own three-dimensional models with toothpicks and different-colored gumdrops or other moderately soft candies.

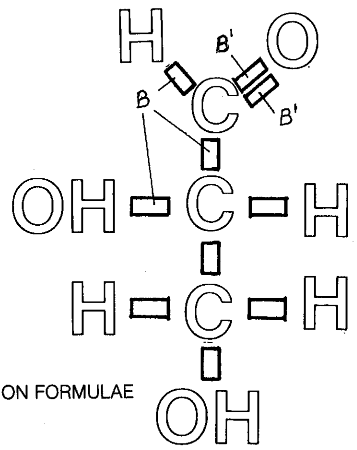
Because of the arrangement of carbon's electron orbitals in three-dimensional space, many compounds of carbon can exist with the identical empirical formula but entirely different arrangements of the same atoms and therefore entirely different chemical properties. Such molecules are called isomers (Greek: *iso,* "same"; *meros,* "parts"). A complete discussion of isomers must be left to a chemistry book, but even a brief study of the molecules of living things introduces us to certain isomers that are exact mirror images of one another, technically known as enantiomers (Greek: *enantios,* "opposite"). If you compare the models of D-glycerose and L-glycerose, you will see that they have the same atoms joined together in the same combinations, but in arrangements that differ in the same way that your right hand differs from your left. They are equal but opposite and are said to be "mirror images" of each other. It is a peculiarity of living things that they use right-handed (D-) isomers of sugars almost exclusively. Left-handed (L-) sugars are extremely rare.

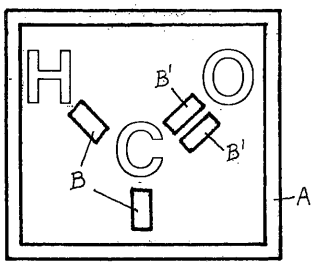
CARBOHYDRATES I.

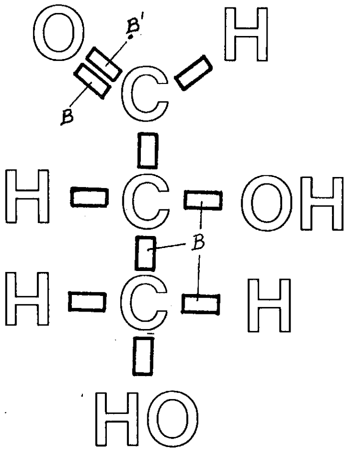
L-GLYCEROSE ISOMER★
EMPIRICAL FORMULA$_{C+H+O}$

D-GLYCEROSE ISOMER★

$C_3H_6O_3$

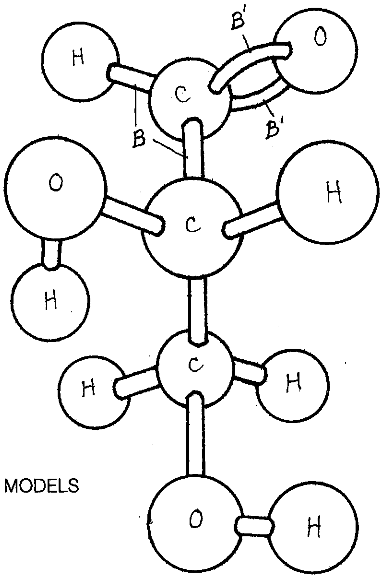




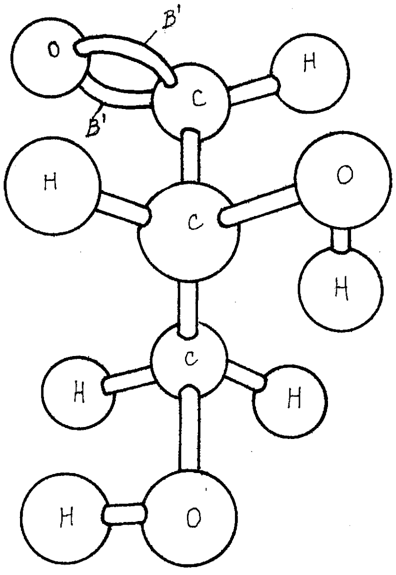


FISCHER PROJECTION FORMULAE

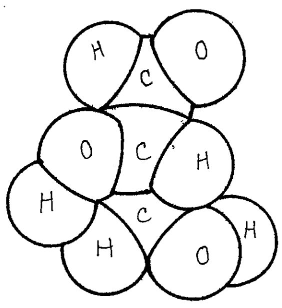
ALDEHYDE$_{A}$
CARBON$_{C}$
HYDROGEN$_{H}$
OXYGEN$_{O}$

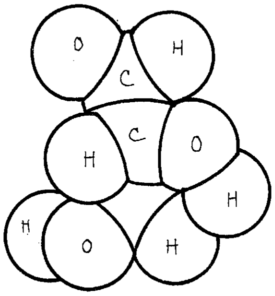


SHARED ELECTRONS★
ONE PAIR$_{B}$
TWO PAIRS$_{B^1}$



BALL-AND-STICK MODELS





SPACE-FILLING MODELS

15
CARBOHYDRATES II

Glucose is the monosaccharide (simple sugar) that circulates in our blood to supply energy to cells throughout the body. It is used as an energy source or a means of energy transport and storage by all other living things as well. Since it is abundant in grapes and in corn, you will often hear it called grape sugar or corn sugar. Like glycerose in Plate 14, glucose has an empirical formula that follows the usual carbohydrate ratio of $(CH_2O)_n$ (with n being 6 in this case), and its number 1 carbon atom is a component of an aldehyde group. Glucose is also important as a building block of many larger molecules, called polysaccharides (Greek: *poly,* "many"), including some giant ones such as cellulose and starch. Only D-glucose is used for all these purposes, so we will not even consider the structure of L-glucose, its mirror-image isomer.

If you are interested only in the biological role of glucose, the preceding paragraph has told you most of what you need to know, and you may want to omit coloring this plate. On the other hand, if you are taking a class in which you are expected to learn some details of the structure of glucose, this plate will help you to understand some concepts that are not well explained in many biology books.

Color the heading D-Glucose and titles C, H, and O, using the same colors as you used in Plate 14. Then color the empirical formula and the Fischer projection formula of glucose.

If you ever try to construct a ball-and-stick model of a glucose molecule from a Fischer projection formula, your model is likely to come out all wrong because there is something that biology and chemistry books almost never tell you. The angles of carbon's electron orbitals make it impossible to arrange such a model so that a projection of it will show all the *carbon* atoms in a straight line unless you zigzag them—but that isn't the way chemists look at a molecule when they make a projection formula.

Color the rolled-up ball-and-stick model, title A, and the chemist's eyes in the four viewing positions around the model. Color also the straight-chain ball-and-stick model with the broken sticks at right. The hydrogen atoms and hydroxyl groups have been omitted from these for clarity.

In making a projection formula, a chemist views each carbon atom separately, with its attached atoms arranged according to the same rule used for glycerose in Plate 14: the carbon atom is rotated so that groups to its right and left project forward, toward the viewer, and atoms above and below it project back, away from the viewer. Thus the molecule is observed one carbon atom at a time, from the viewpoints indicated by the "*chemist's eyes*" in the plate. To get a ball-and-stick model into a position where it would project properly, you would have to break all the sticks joining the carbon atoms (or replace them with something very flexible). To most of us, this seems a funny way to view a molecule, but that is the way a Fischer projection is drawn.

Color the headings α-D-Glucose and β-D-Glucose and each of the remaining structural formulae as you come to them in the reading below.

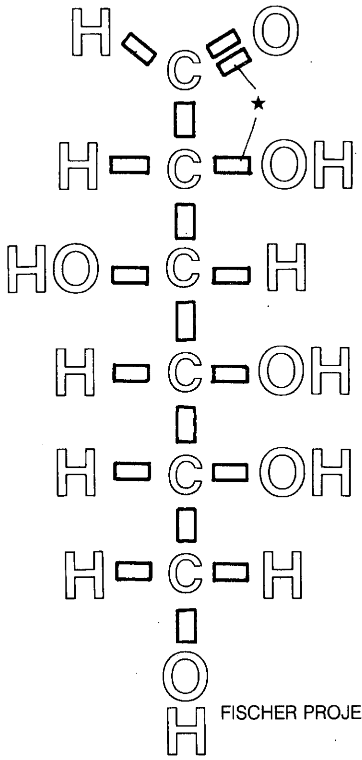
Glucose in a living animal or plant is virtually always dissolved in water, and the molecule bends and folds as it collides with other molecules. Whenever it folds far enough to bring carbon 1 close to carbon 5, one hydrogen atom and several electrons change places to rearrange the molecule into a closed ring, as shown in the lower part of the plate. Depending on which of the two bonds is disrupted between carbon 1 and its oxygen atom, this ring structure of glucose can take two forms, known as alpha (α) and beta (β). Any single molecule is constantly changing from one form to another, and any solution of glucose in water consists of all three forms, approximately 36 percent α ring, 64 percent β ring, and less than 1 percent straight chain form. (Other monosaccharides form similar rings.)

When we diagram the ring structures, the "chair" formula is useful because it shows the bond angles accurately. The Haworth projection formula is less accurate but easier to draw, so it is widely used. Note that the carbon atoms in this projection are not represented by a letter. The user must remember that each intersection of the lines represents a carbon atom. (The chair formula can also be drawn with only intersections to represent carbon.)

The space-filling model shows approximately what we think the electron clouds (orbitals) would look like if we could see them.

CARBOHYDRATES II.

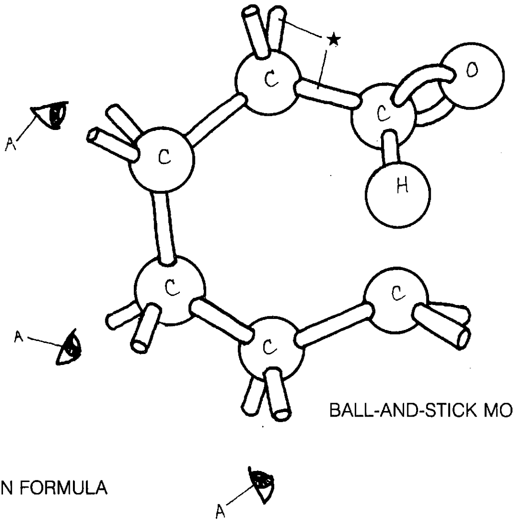
D-GLUCOSE★ CARBON C HYDROGEN H OXYGEN O



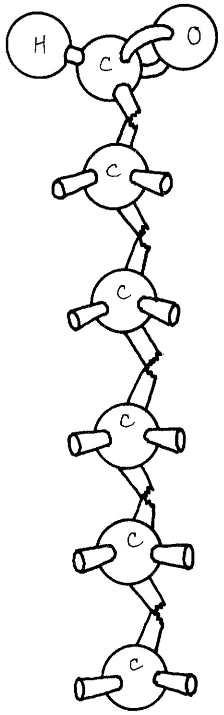
FISCHER PROJECTION FORMULA

$C_6H_{12}O_6$

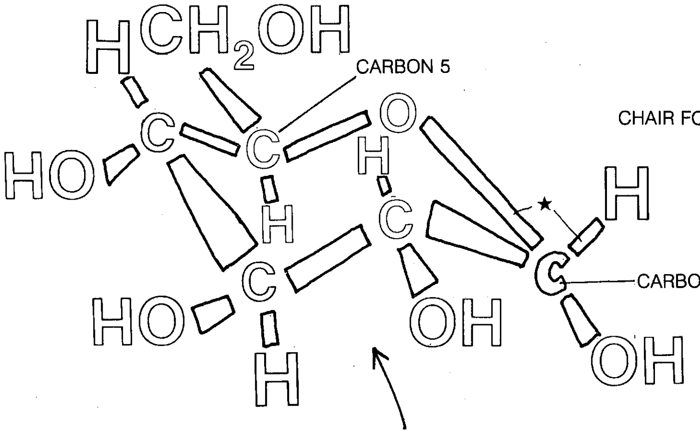
A CHEMIST'S EYE A

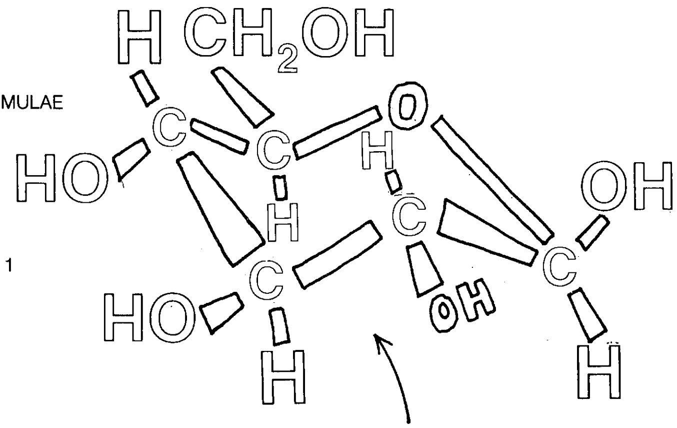


BALL-AND-STICK MODEL



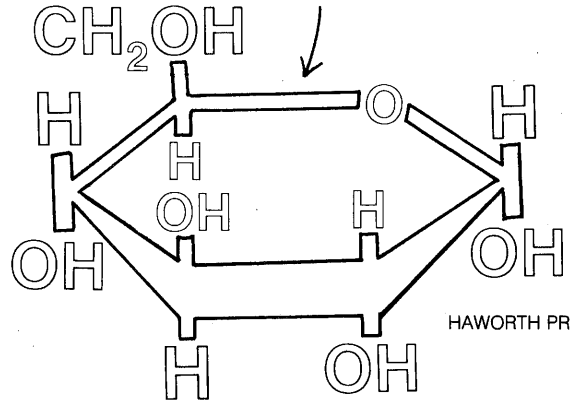
CHAIR FORMULAE



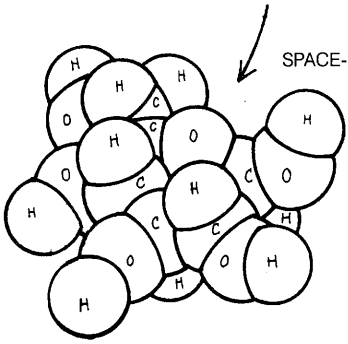


α-D-GLUCOSE★

β-D-GLUCOSE★



HAWORTH PROJECTION



SPACE-FILLING MODEL

16
CARBOHYDRATES III

In this plate we see how monosaccharides (single sugars) are joined together to make a wide variety of larger carbohydrates.

Color titles A through E and the related illustration. In this plate you need only color the whole molecules, so choose pale colors. The broken ring (D) around the lower glucose molecules illustrates that maltose (D) is formed from two glucose molecules. The ring does not actually exist in a molecule.

A *disaccharide* is formed by the removal of a hydrogen atom from one *monosaccharide molecule* and a hydroxyl (OH) group from another monosaccharide molecule to form a *water molecule.* The two monosaccharides are then joined together by a covalent bond to form a disaccharide. Since *water* is removed (dehydration) and the two monosaccharides are "condensed" into a single molecule, this reaction is commonly called a *"dehydration condensation"* or "dehydration synthesis" (*synthesis,* "putting together"), indicated by arrow B. This same type of condensation is used by living things to assemble proteins, lipids, and nucleic acids from their subunits, as we will see later. The reverse of this is called *hydrolysis* because a water molecule is broken in the process (Greek: *hydro,* "water"; *lysis,* "loosening" or "breaking").

The first section of this plate illustrates the dehydration condensation of two molecules of *glucose,* the principal sugar circulating in your blood, to form a molecule of the disaccharide *maltose.* Maltose is abundant in malt (germinated grain used in brewing) and is also produced when an enzyme (ptyalin) in your saliva breaks down starch in your mouth. Glucose and other monosaccharides are condensed in various combinations to make different disaccharides or polysaccharides (Greek: *poly,* "many").

Color the heading Disaccharides, the associated titles, and the sucrose and lactose molecules. Again, the broken rings (F and H) are for illustrative purposes only.

Sucrose is a disaccharide that is familiar as common table sugar, usually obtained from sugarcane or sugar beets. It is formed by the dehydration condensation of a molecule of glucose and a molecule of *fructose,* which is a monosaccharide abundant in many kinds of fruit. *Lactose* is a disaccharide that is abundant in milk. It is formed by the dehydration condensation of a molecule of glucose and a molecule of *galactose.* Galactose has a structure that is identical to glucose except for a reversal of the hydrogen and hydroxyl (OH) groups attached to carbon 4.

Color the heading Polysaccharides and titles J and K. Color over the amylose and amylopectin molecules.

Starch is a mixture of two different polysaccharides, *amylose* and *amylopectin.* Each is composed of hundreds of glucose molecules joined together. Starch provides plants with a good means of storing energy. In amylose, the glucose molecules are joined together in one long, unbranched chain that coils up into a helix in the watery environment found in living things. In amylopectin, the chain is branched and sometimes forms a complex network. All of the glucose molecules are in the alpha ring form, so the bonds linking them together are known as alpha linkages. Humans and other animals are able to digest both amylose and amylopectin, so they serve as a good source of energy.

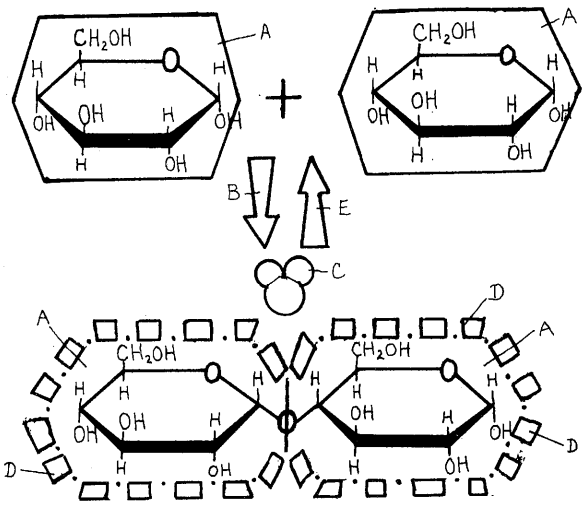
Color title L, and color over the glycogen molecule.

Glycogen is commonly called "animal starch," and that is a very appropriate name for it. It is exactly like amylopectin except that its chain branches at closer intervals and it apparently does not link up with other glycogen molecules to form networks. Its function is also the same. It serves as a means of storing large amounts of energy. After a meal, when you have more glucose in your blood than you need, your liver stores a great deal of glucose in the form of glycogen. Hours later, when your blood glucose begins to drop, the liver replenishes the supply. Muscle also stores glycogen to have an immediate supply of energy for emergencies.

Color title M, and color over the cellulose molecules.

Cellulose is very much like amylose in consisting of a straight chain of glucose molecules, but the chains are much longer (up to 4000 glucose molecules in some plant fibers), and all the glucose is in the beta ring form. The bonds joining them together are therefore beta linkages, and it happens that no animal has an enzyme capable of breaking those linkages to make the glucose available for energy. Cattle and similar animals have bacteria in their digestive tracts that digest the cellulose for them, but for humans and most other animals, cellulose is completely indigestible. Cellulose does not form a helix like amylose; it joins to other cellulose molecules by means of hydrogen bonds, making an immense complex that is totally insoluble in water.

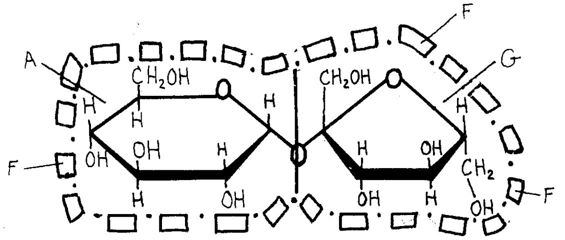
CARBOHYDRATES III.



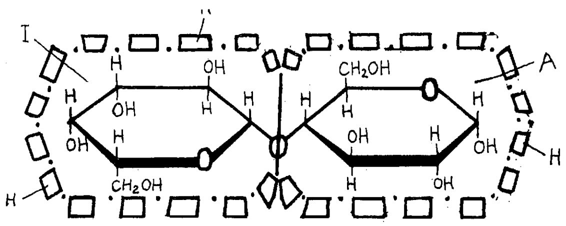
GLUCOSE
(MONOSACCHARIDE) A
DEHYDRATION
CONDENSATION B
WATER C
MALTOSE
(DISACCHARIDE) D
HYDROLYSIS E

DISACCHARIDES★

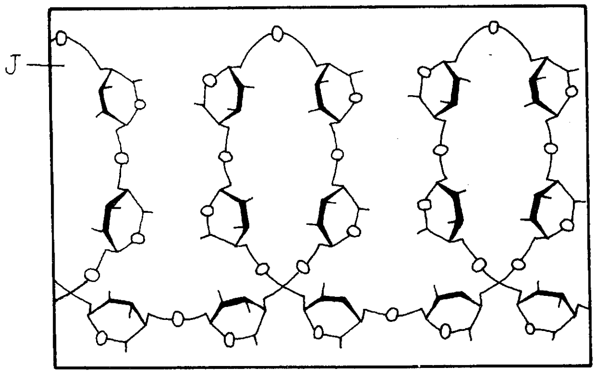
SUCROSE F
GLUCOSE A + FRUCTOSE G



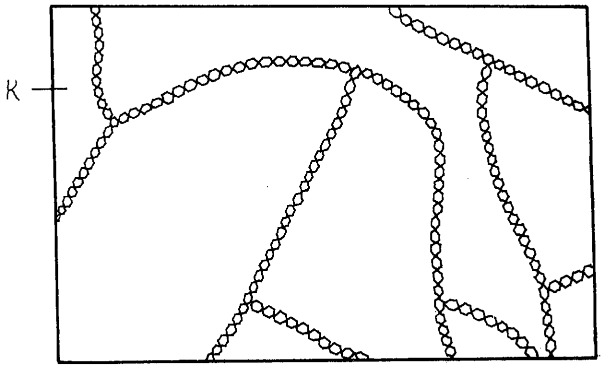
LACTOSE H
GALACTOSE I + GLUCOSE A

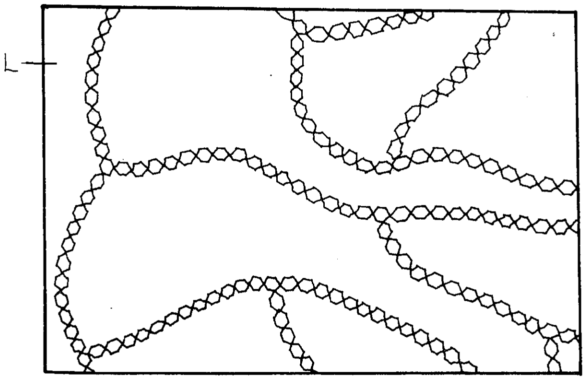


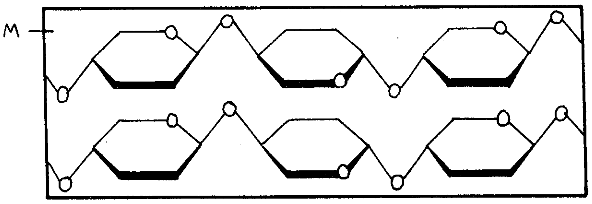
POLYSACCHARIDES★



AMYLOSE J
AMYLOPECTIN K
GLYCOGEN L
CELLULOSE M







17

LIPIDS

Lipids are fats, waxes, and similar molecules that do not dissolve well in water.

Color titles A, B, C, H, O, D, and D^1 and the Space-Filling Model headings. Color the projection formulae and the space-filling models of glycerol and the saturated and unsaturated fatty acids. It is recommended that you use the same colors as in previous plates for the carbon, hydrogen, and oxygen atoms. Choose light colors for A, B, and D.

Fats are composed of *glycerol* and *fatty acids.* Glycerol always has three *carbon atoms* and three hydroxyl (OH) groups, but there are several dozen kinds of fatty acids, ranging in size from 4 carbon atoms to 24. On one end of a fatty acid we find a carbon atom with a double bond to an oxygen atom and a single bond to a hydroxyl group. This entire group of four atoms, often written as —COOH, is called a carboxyl group and is able to ionize to release a hydrogen ion into solution, thus acting as an acid. (The ionized carboxyl group is symbolized as $—COO^-$.) In any group of such molecules, only a few are ionized at any one time, so fatty acids are all weak acids. All the rest of a fatty acid molecule is pure hydrocarbon (hydrogen and carbon). Fatty acids are designated as *saturated* or *unsaturated* according to whether they are filled to capacity with hydrogen atoms or not. In a saturated fatty acid, all of the carbon atoms are joined to one another by single bonds, and each one (other than the carboxyl carbon) is bonded to at least two hydrogen atoms. (The one on the end has three.) In an unsaturated fatty acid, at least one pair of carbon atoms is joined by a *double bond,* so that each of those carbon atoms is bonded to only one hydrogen atom, leaving the fatty acid with at least two fewer hydrogen atoms than it would have if it were saturated. The double bond often throws a kink in the hydrocarbon chain as shown in the space-filling model here.

Color title E and the projection formula of the triglyceride. The broken ring (E) is to illustrate that the triglyceride is composed of glycerol, saturated fatty acids, and an unsaturated fatty acid.

A fat—chemically known as a *triglyceride*—consists of a molecule of glycerol joined to three fatty acid molecules by the same kind of dehydration condensation we saw in the formation of disaccharides and polysaccharides. The three fatty acids may be all the same or any combination of different ones. Note that in the triglyceride illustrated, two of the fatty acids are saturated and one is unsaturated. This would be called a monounsaturated fat, because it is unsaturated (has a carbon double bond) at only one point in the entire triglyceride molecule. If it were unsaturated at two or more points, it would be called a polyunsaturated fat. Since hydrocarbons are nonpolar, the entire triglyceride molecule is nonpolar except for a slight polarity around the oxygen atoms. For this reason, triglycerides (fats) are not much attracted to water molecules. If you have ever tried to wash butter or other animal fat off of your hands with just water, you have noticed that.

Color titles F, G, and H, and the projection formula of the phospholipid. The broken ring (F) is for illustrative purposes only.

In molecular structure *phospholipids* are like triglycerides except that in place of the third fatty acid they have a *phosphate group* and some other *polar group.* This results in a molecule with a dual nature. The hydrocarbon chains of the fatty acids are not attracted to water and are called hydrophobic ("water-fearing"). The phosphate and the other group are attracted to water and are called hydrophilic ("water-loving"). It is precisely this dual nature that allows phospholipids to form membranes, as we shall see in a later plate.

Color title I and the projection formula of the steroid nucleus.

The *steroid nucleus* consists of four interlocking rings of carbon atoms with numerous hydrogen atoms attached. It forms the core of a wide variety of important molecules including many hormones, which differ in the groups of atoms substituted for the hydrogen atoms at various points on the rings.

Color titles J and K and the projection formula of beeswax. The broken ring (J) is for illustrative purposes only.

Waxes provide protective coatings for various plant and animal tissues and for bees to make honeycombs. They are formed by the dehydration condensation of a long-chain *alcohol* (hydrocarbon with a hydroxyl group at one end) and a long-chain fatty acid.

Other, less common lipids (not illustrated) combine fatty acids with various other groups, such as sugars and amino acids.

LIPIDS.

GLYCEROL

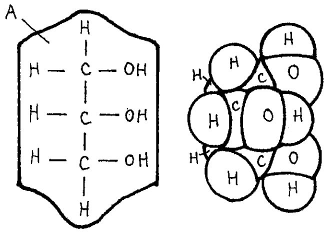
PROJECTION FORMULA$_{A}$

SPACE-FILLING MODEL★

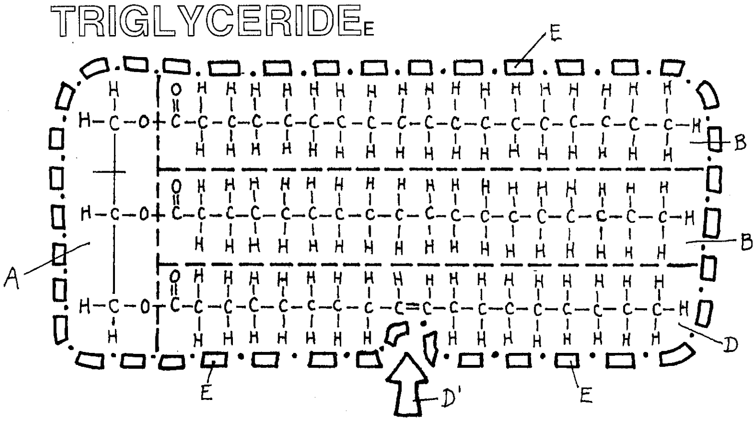
CARBON$_{C}$

HYDROGEN$_{H}$

OXYGEN$_{O}$



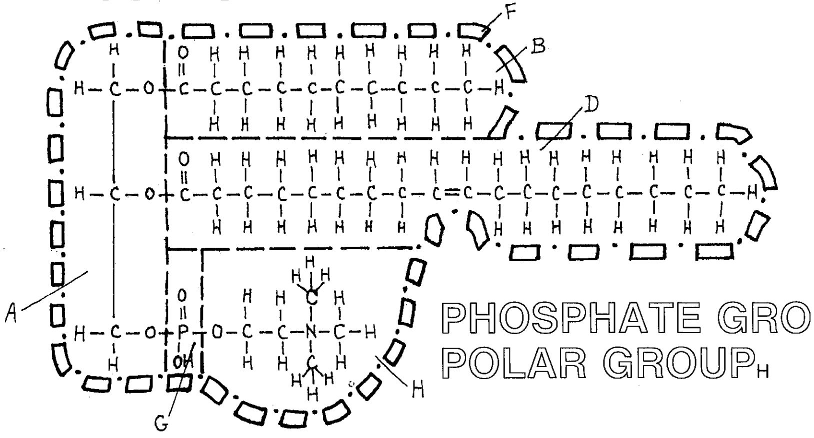
TRIGLYCERIDE$_{E}$



PHOSPHOLIPID$_{F}$

PHOSPHATE GROUP$_{G}$

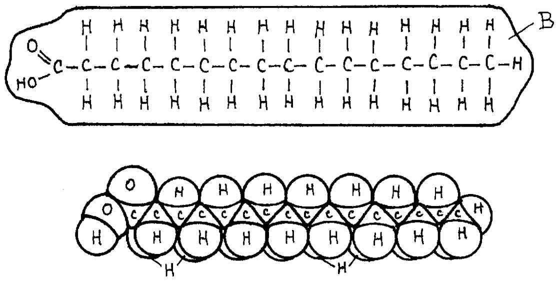
POLAR GROUP$_{H}$



SATURATED FATTY ACID

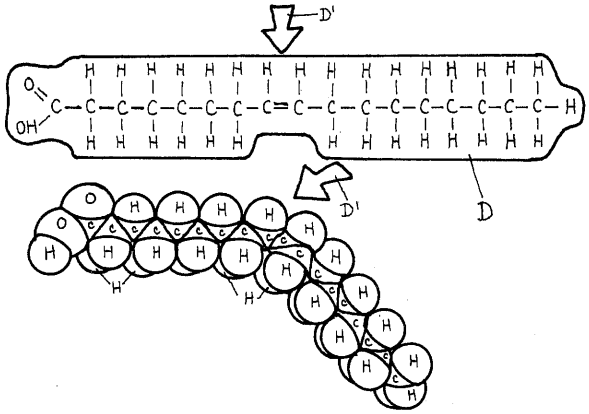
PROJECTION FORMULA$_{B}$

SPACE-FILLING MODEL★

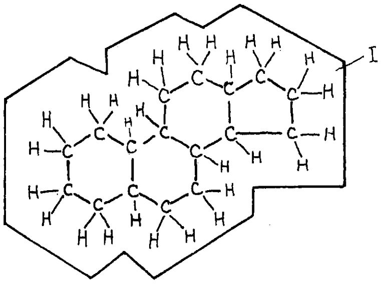


UNSATURATED FATTY ACID$_{D}$

CARBON DOUBLE BOND$_{D'}$

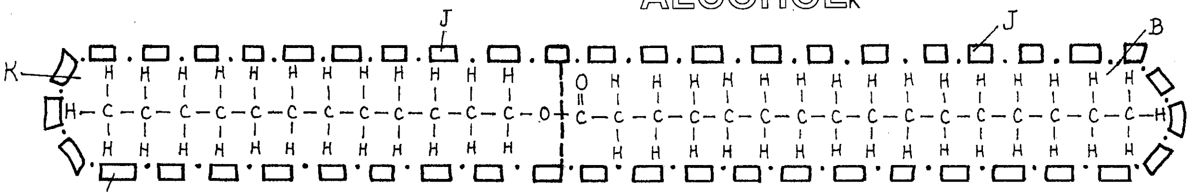


STEROID NUCLEUS$_{I}$



BEESWAX$_{J}$

ALCOHOL$_{K}$



18

INTRODUCTION TO PROTEIN

Protein gets its name from a Greek word meaning "first" or "primary" because it is the material of primary importance in every process we associate with being alive. Virtually none of the chemical reactions in a living thing would occur at any useful speed if it were not for those specialized protein molecules called enzymes. Other proteins serve as transport molecules, carrying things in the blood or across membranes or transporting electrons that are removed or added in important chemical reactions. Proteins are the main structural components of claws, hooves, and hair as well as the tough surface layer of skin. Contraction of muscle and movement within living cells is accomplished by protein. Many of the chemical messengers we call hormones are proteins, as are the antibodies that protect us from disease.

Color the heading Amino Acid and titles C through N using the same colors as in previous plates. Now color the ball-and-stick model and the space-filling model at the top of the plate. The sticks that represent shared electrons (bonds) are to be colored gray. Leave the side groups uncolored for now.

Proteins are made up primarily (or exclusively, in some cases) of long chains of amino acids. Amino acids (here illustrated by L-alanine) consist of a two-carbon portion that is common to all amino acids and a side group, which varies from one amino acid to the next. *Carbon* 1 is part of a carboxyl group (—COOH). The carboxyl group gives these molecules their acid properties by dissociating to release a hydrogen ion (proton). Carbon 2 has a nitrogen-containing amino group (NH_2).

In contrast to the situation in carbohydrates, where the right-handed or D-isomers are used for nearly everything, we find that proteins are made exclusively of the left-handed or L-isomers of amino acids. (D-amino acids are found in some antibiotics but not in proteins.)

Color the title ionization and the projection formulae of un-ionized alanine and the alanine zwitterion. Again, the gray bars are shared pairs of electrons.

Under the conditions found in living cells, nearly every molecule of any amino acid is doubly *ionized:* the carboxyl group releases a *hydrogen* ion and becomes negatively charged, while the amino group picks up a hydrogen ion and becomes positively charged. The resulting double ion is called a zwitterion (German: *zwitter,* "hybrid"). Note that in the ionized carboxyl group we use one solid line and one broken line to join each oxygen atom to carbon 1. This is to indicate that each *oxygen* shares 3 electrons (1½ pairs) with the carbon atom. Thus the two oxygen atoms share the negative charge. These are true covalent bonds because a sharing of electrons is involved, but they are unusual in sharing one pair of electrons among one carbon atom and two oxygen atoms. (For convenience, projection formulae are often written as if all the negative charge were on one oxygen atom, but it isn't so).

Color the side groups of the top illustrations. Color the heading Peptide Formation and title S. The conventional color for sulfur is yellow. Then color the L-alanine and the L-cysteine in the bottom half of the plate.

More than 50 different amino acids have been discovered in living things, but only 20 of them are used to make proteins. Of the 20, 19 have exactly the same arrangement of atoms around carbon atoms 1 and 2 that you see here in L-alanine. (The twentieth is almost the same.) They differ in their side groups, which are the groups attached to carbon 2. They are called side groups because they stick out to the side of the long chain that is formed when numerous amino acids are joined together to make a protein. Alanine's side group consists of a carbon atom with three hydrogens attached (known as a methyl group). (Notice that in the lower drawing, the molecule has been flopped over 90 degrees to the right for illustration purposes.) Cysteine has a side group that is similar but includes a *sulfur* atom. Other amino acids have side groups that range from a single hydrogen atom up to a double ring of carbon and nitrogen atoms, as you can see in the next plate.

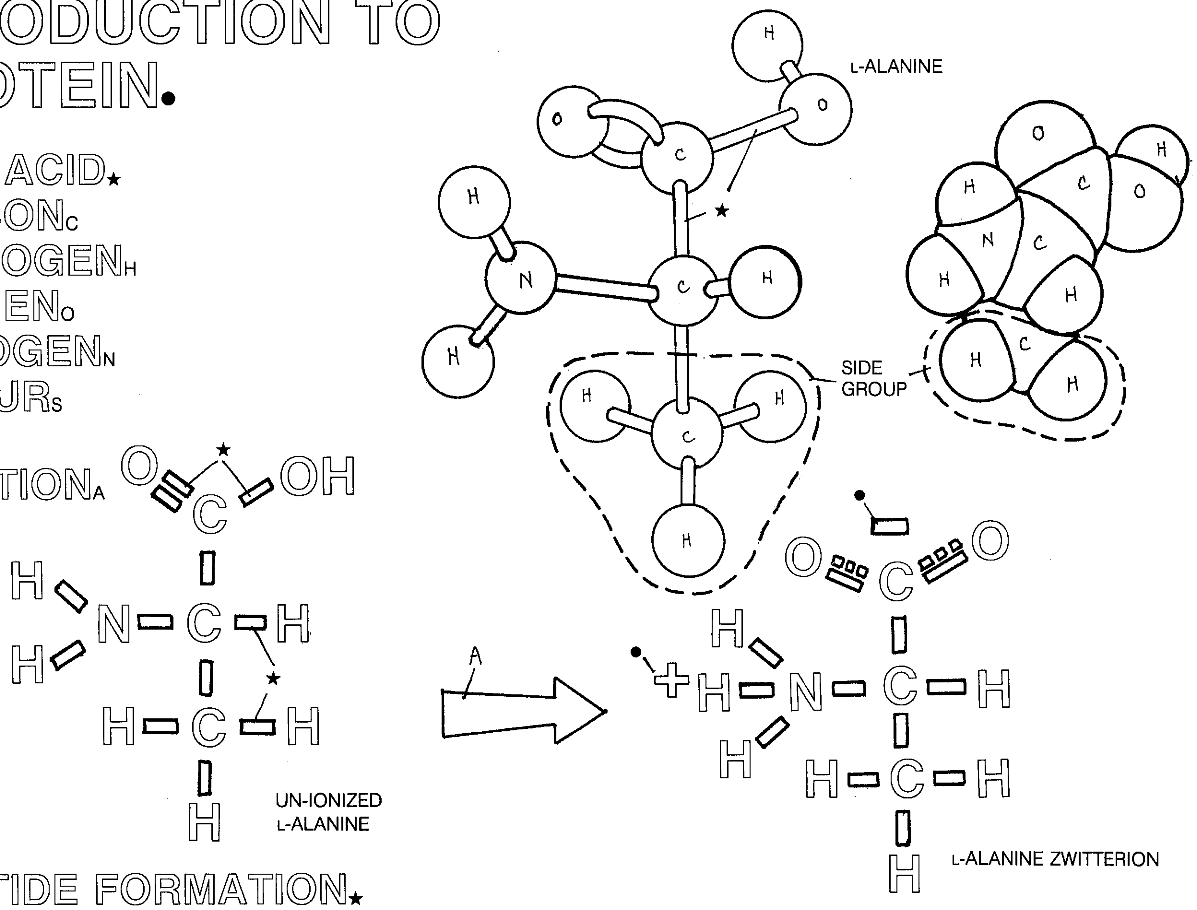
Color titles B, D, and E, the arrows (B and D), the dipeptide, and the water molecule.

Just as with carbohydrates and fats, proteins are assembled by a *dehydration condensation* of their subunits. The covalent bond joining two amino acids in this way is called a *peptide bond.* The resulting molecule is called a dipeptide. If we add one more amino acid to the chain in the same way, we will have a tripeptide. When we have many amino acids joined in a chain in this way, the molecule is called a polypeptide. A functional protein molecule may consist of a single polypeptide or a number of polypeptides joined together. It may also include some nonpolypeptide portions.

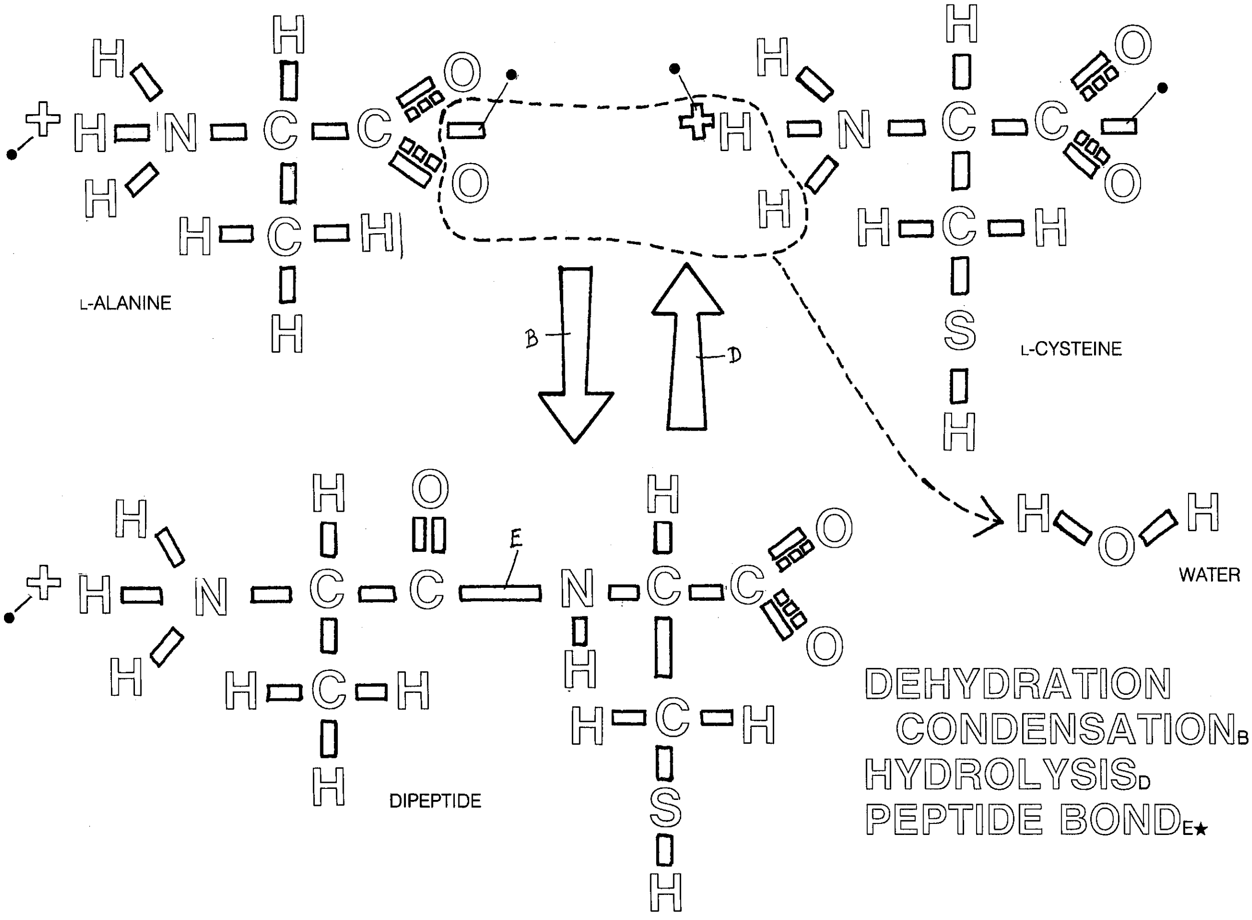
INTRODUCTION TO PROTEIN.

AMINO ACID★
CARBON$_{C}$
HYDROGEN$_{H}$
OXYGEN$_{O}$
NITROGEN$_{N}$
SULFUR$_{S}$

IONIZATION$_{A}$



PEPTIDE FORMATION★



DEHYDRATION
CONDENSATION$_{B}$
HYDROLYSIS$_{D}$
PEPTIDE BOND$_{E}$★

19
AMINO ACIDS

In this plate the amino acids are shown with their carboxyl and amino groups ionized (zwitterions), since most of them are in this state at the pH found in most living tissues. The carboxyl group releases a hydrogen ion to become negatively charged, and the amino group picks up a hydrogen ion to become positively charged.

Color the heading Nonpolar Amino Acids and titles A and B. Color over the projection formulae of all the amino acids in this class, using one light color for the common portion (A) and a second light color for the distinctive side group (B).

The *amino acids* in the first group are designated as *nonpolar* because their side groups are nonpolar, and the side groups determine the behavior of the finished protein molecule. The nonpolar *side groups* will not be attracted to water and will tend to clump together in the presence of water, just as oil molecules clump together to form droplets of oil in the watery portion of a salad dressing. How this influences the three-dimensional structure of the protein molecule and therefore its behavior will be introduced in the next plate.

Note that the last acid in this group, proline, does not have a complete amino group because its nitrogen atom is connected back to carbon 5 to form a ring. (Technically, it is an imino acid, not an amino acid.) We will see in Plate 21 that this also has an important influence on the structure of completed protein.

Color the heading Polar, Non-Ionic Amino Acids and title C. Color over the projection formulae of all the amino acids in this class with A and a light color for C.

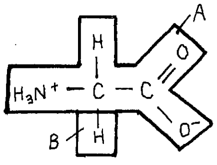
These amino acids have *side groups* that are *polar* in the same sense that a water molecule is polar: one part has a weak positive charge and another part has a weak negative charge. They are said to be non-ionic because their electric charges are only a small fraction of the full unit of charge to be found on an ion. These side groups are strongly attracted to water, to ions, and to one another.

Color the heading Ionic Amino Acids and title D. Color over the projection formulae of the amino acids in this class. Use a light color for D.

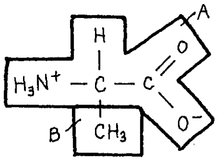
The *side groups* of these amino acids are fully charged *(ionic)* under most conditions, although the pH of the surrounding solution can change this. As a result, they are strongly attracted to the ionic side groups of other amino acids as well as to water and to polar side groups but not to nonpolar ones.

AMINO ACIDS•

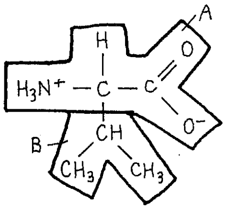
NONPOLAR AMINO ACIDS★
COMMON PORTION A
NONPOLAR SIDE GROUP B



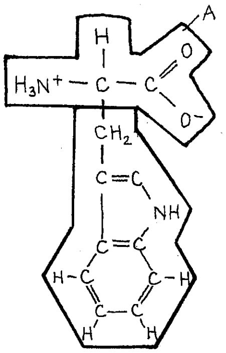
GLYCINE



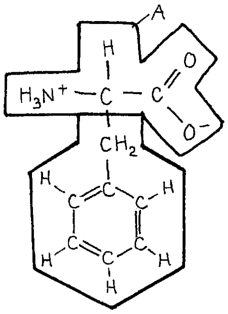
ALANINE



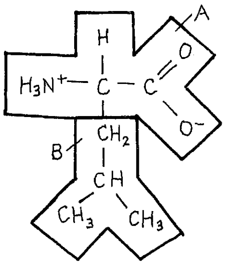
VALINE



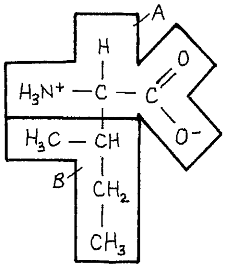
TRYPTOPHAN



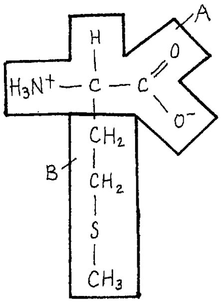
PHENYLALANINE



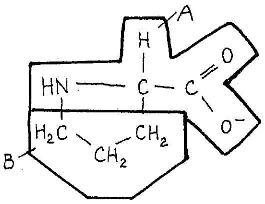
LEUCINE



ISOLEUCINE

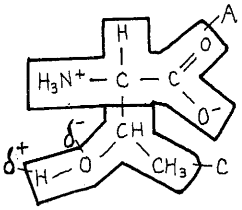


METHIONINE

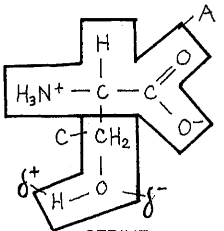


PROLINE

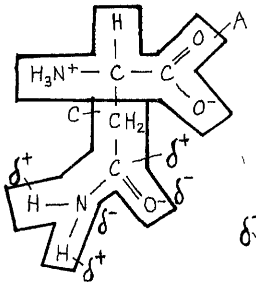
POLAR NON-IONIC AMINO ACIDS★
POLAR SIDE GROUP C



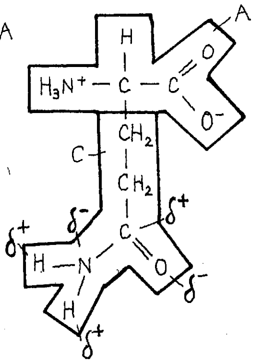
THREONINE



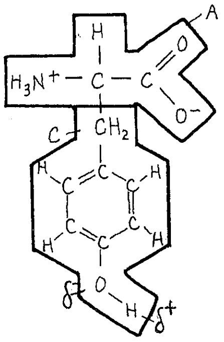
SERINE



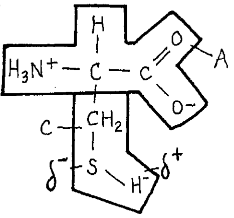
ASPARAGINE



GLUTAMINE

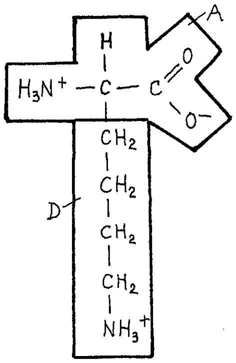


TYROSINE

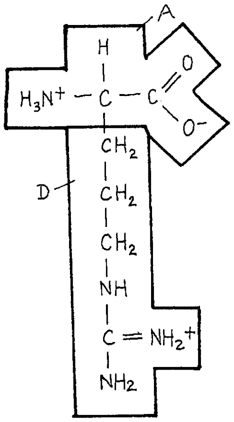


CYSTEINE

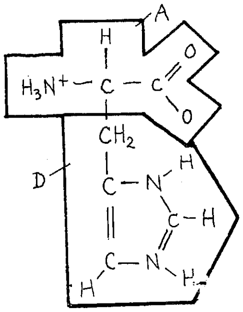
IONIC AMINO ACIDS★
IONIC SIDE GROUP D



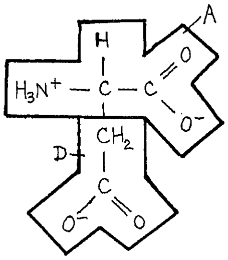
LYSINE



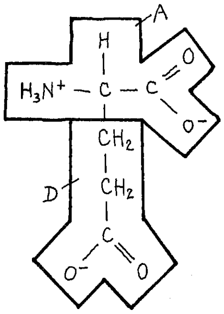
ARGININE



HISTIDINE



ASPARTIC ACID



GLUTAMIC ACID