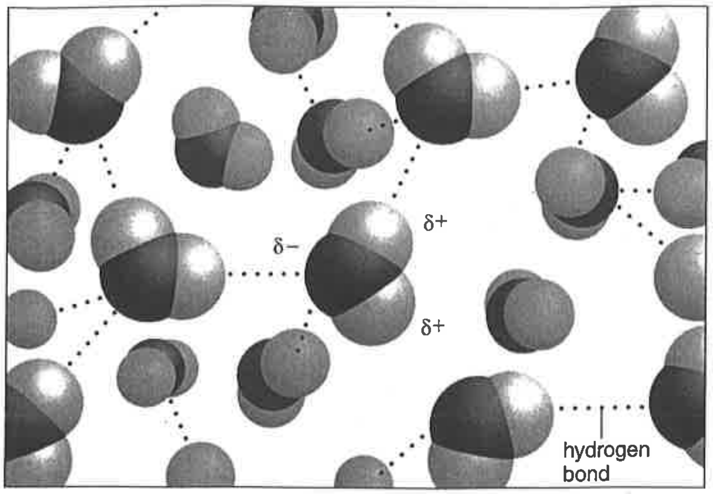
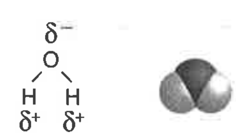


Figure 2.8 Hydrogen bonding between water molecules. The polarity of the water molecules allows hydrogen bonds (dotted lines) to form between the molecules.

2.3 Water and Living Things

Water is the most abundant molecule in living organisms, and it makes up about 60–70% of the total body weight of most organisms. We will see that the physical and chemical properties of water make life possible as we know it.

Water is a polar molecule; the oxygen end of the molecule has a slight negative charge, and the hydrogen end has a slight positive charge:



The diagram on the left shows the structural formula of water and the one on the right shows the space-filling model of water.

In polar molecules, covalently bonded atoms share electrons unevenly; that is, the electrons spend more time circling the nucleus of one atom than circling the other. In water, the electrons spend more time circling the larger oxygen (O) than the smaller hydrogen (H) atoms.

In water, the negative end and positive ends of the molecules attract one another. Each oxygen forms loose bonds to hydrogen atoms of two other water molecules (Fig. 2.8). These bonds are called hydrogen bonds. A **hydrogen bond** occurs whenever a covalently bonded hydrogen is positive and attracted to a negatively charged atom some distance away. A hydrogen bond is represented by a dotted line in Figure 2.8 because it is relatively weak and can be broken rather easily.

Properties of Water

Because of their polarity and hydrogen bonding, water mo ecules are cohesive and cling together. Polarity and hydr gen bonding causes water to have many characteristi beneficial to life.

1. Water is a liquid at room temperature. Therefore we a able to drink it, cook with it, and bathe in it.

Compounds with low molecular weights are usually gas at room temperature. For example, oxygen (O_2) with a m lecular weight of 32 is a gas, but water with a molecul weight of 18 is a liquid. The hydrogen bonding between w ter molecules keeps water a liquid and not a gas at roo temperature. Water does not boil and become a gas un 100°C, one of the reference points for the Celsius temper ture scale. (See Appendix C.) Without hydrogen bonding b tween water molecules, our body fluids and indeed o bodies would be gaseous!

2. Water is the universal solvent for polar (charged) molecules and thereby facilitates chemical reactions both outside of and within our bodies.

When a salt such as sodium chloride (NaCl) is put into w ter, the negative ends of the water molecules are attracted the sodium ions, and the positive ends of the water mol cules are attracted to the chloride ions. This causes t sodium ions and the chloride ions to separate and to di solve in water:

The salt NaCl dissolves in water

When ions and molecules disperse in water, they mo about and collide, allowing reactions to occur. Therefor water is a solvent that facilitates chemical reactions.

Ions and molecules that interact with water are said be **hydrophilic.** Nonionized and nonpolar molecules that c not interact with water are said to be **hydrophobic.**

3. Water molecules are cohesive and therefore liquids wi fill vessels.

Water molecules cling together because of hydrogen bon ing, and yet, water flows freely. This property allows di solved and suspended molecules to be evenly distribute throughout a system. Therefore, water is an excellent tran port medium. Within our bodies, blood which fills ou arteries and veins is 92% water. Blood transports oxyge and nutrients to the cells and removes wastes such as carbo dioxide.

Figure 2.10 Dissociation of water molecules.
Dissociation produces an equal number of hydrogen ions (H^+) and hydroxide ions (OH^-). (These illustrations are not meant to be mathematically accurate.)

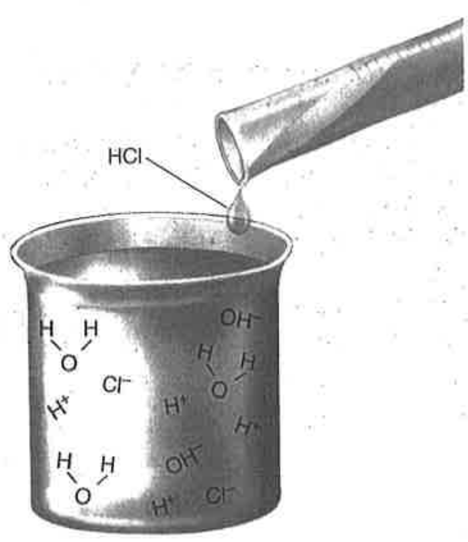


Figure 2.11 Addition of hydrochloric acid (HCl).
HCl releases hydrogen ions (H^+) as it dissociates. The addition of HCl to water results in a solution with more H^+ than OH^-.

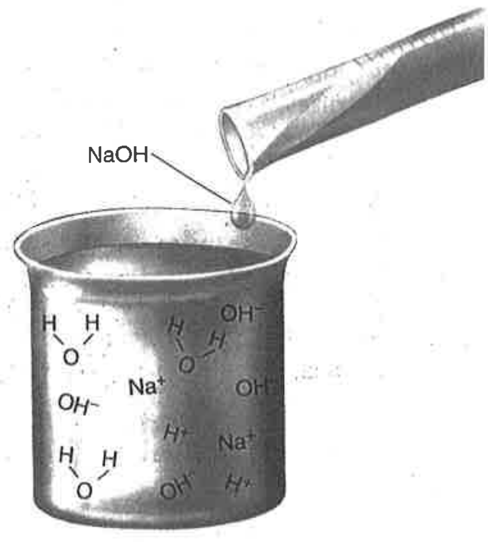


Figure 2.12 Addition of sodium hydroxide (NaOH), a base.
NaOH releases OH^- as it dissociates. The addition of NaOH to water results in a solution with more OH^- than H^+.

Acidic and Basic Solutions

When water dissociates (breaks up), it releases an equal number of hydrogen ions (H^+) and hydroxide ions (OH^-).

$$\underset{\text{water}}{H{-}O{-}H} \rightleftharpoons \underset{\text{hydrogen ion}}{H^+} + \underset{\text{hydroxide ion}}{OH^-}$$

Only a few water molecules at a time are dissociated (Fig. 2.10). The actual number of ions is 10^{-7} moles/liter. A mole is a unit of scientific measurement for atoms, ions, and molecules.[1]

Acidic Solutions

Lemon juice, vinegar, tomato juice , and coffee are all familiar acidic solutions. What do they have in common? Acidic solutions have a sharp or sour taste, and therefore we sometimes associate them with indigestion. To a chemist, **acids** are molecules that dissociate in water, releasing hydrogen ions (H^+). For example, an important acid in the laboratory is hydrochloric acid (HCl), which dissociates in this manner:

$$HCl \rightarrow H^+ + Cl^-$$

Dissociation is almost complete; therefore, this is called a strong acid. When hydrochloric acid is added to a beaker of water, the number of hydrogen ions increases (Fig. 2.11).

Basic Solutions

Milk of magnesia and ammonia are common basic solution that most people have heard of. Bases have a bitter tast and feel slippery when in water. To a chemist, **bases** ar molecules that either take up hydrogen ions (H^+) or releas hydroxide ions (OH^-). For example, an important inorgani base is sodium hydroxide (NaOH), which dissociates in thi manner:

$$NaOH \rightarrow Na^+ + OH^-$$

Dissociation is almost complete; therefore sodium hydro› ide is called a strong base. If sodium hydroxide is added to beaker of water, the number of hydroxide ions increase (Fig. 2.12).

It is not recommended that you taste a strong acid c base, because they are quite destructive to cells. Any co tainer of household cleanser like ammonia has a poiso symbol and carries a strong warning not to ingest th product.

The Litmus Test

A simple laboratory test for acids and bases is called the li mus test. Litmus is a vegetable dye that changes color fro blue to red in the presence of an acid and from red to blue i the presence of a base. The litmus test has become a comm figure of speech, as when you hear a commentator say, "Th litmus test for a Republican is . . ."

[1] A mole is the same amount of atoms, molecules, ions as the number of atoms in exactly 12 grams of ^{12}C.

The pH Scale

The **pH scale**[2] is used to indicate the acidity and basicity (alkalinity) of a solution. Since there are normally few hydrogen ions (H^+) in a solution, the pH scale was devised to eliminate the use of cumbersome numbers. For example, the possible hydrogen ion concentrations of a solution are on the left of this listing and the pH is on the right:

moles/liter

$1 \leftrightarrow 10^{-6}\,[H^+] = \text{pH } 6$ (an acid)
$1 \leftrightarrow 10^{-7}\,[H^+] = \text{pH } 7$ (neutral)
$1 \leftrightarrow 10^{-8}\,[H^+] = \text{pH } 8$ (a base)

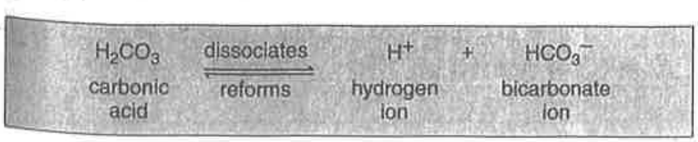
Pure water (HOH) has an equal number of hydrogen ions (H^+) and hydroxide ions (OH^-); therefore, one of each is released when water dissociates. One mole of pure water contains only 10^{-7} moles/liter of hydrogen ions; therefore, a pH of exactly 7 is neutral pH. At a pH of 7 there is an equal number of hydrogen ions and hydroxide ions. Above pH 7 there are more hydroxide ions than hydrogen ions, and below pH 7 there are more hydrogen ions than hydroxide ions. Therefore any solution with a pH below 7 is an acidic solution and any solution with a pH above 7 is a basic solution. Also, as we move down the pH scale from 14 to 0, each unit has 10 times the $[H^+]$ of the previous unit (Fig. 2.13). As we move up the pH scale from 0 to 14, each unit has 10 times the $[OH^-]$ of the previous unit.

As discussed in the Ecology reading on page 30, there have been detrimental environmental consequences on nonliving and living things as rain and snow have become more acidic during modern times. In plants and animals, including ourselves, pH needs to be maintained within a narrow range or there are health consequences.

Buffers

Buffers resist pH changes because they are chemicals or combinations of chemicals that can take up excess hydrogen ions (H^+) or hydroxide ions (OH^-). Many commercial products like Bufferin or shampoos or deodorants are buffered as an added incentive to have us buy them.

Our cells and body fluids are naturally buffered and for that reason the pH of our blood when we are healthy is always about 7.4. The main buffer in blood is a combination of carbonic acid and bicarbonate ions which are a dissociation product of carbonic acid. Carbonic acid (H_2CO_3) is a weak acid that minimally dissociates and then reforms in the following manner:



[2]pH is defined as the negative logarithm of the molar concentration of the hydrogen ion $[H^+]$.

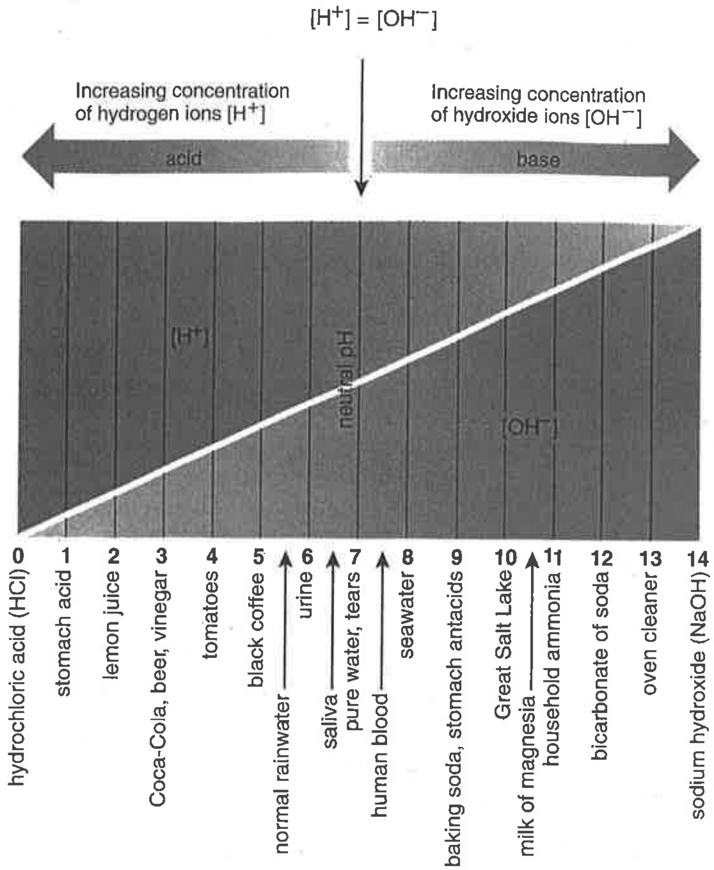


Figure 2.13 **The pH scale.**
The diagonal line indicates the proportionate concentration of hydrogen ions (H^+) to hydroxide ions (OH^-) at each pH value. Any pH value above 7 is basic, while any pH value below 7 is acidic.

When hydrogen ions (H^+) are added to blood, the following reaction occurs:

$$H^+ + HCO_3^- \rightarrow H_2CO_3$$

When hydroxide ions (OH^-) are added to blood, this reaction occurs:

$$OH^- + H_2CO_3 \rightarrow HCO_3^- + H_2O$$

These reactions prevent any significant change in blood pH.

Acids have a pH that is less than 7, and bases have a pH that is greater than 7. Buffers, which can combine with both hydrogen ions and hydroxide ions, resist pH changes.

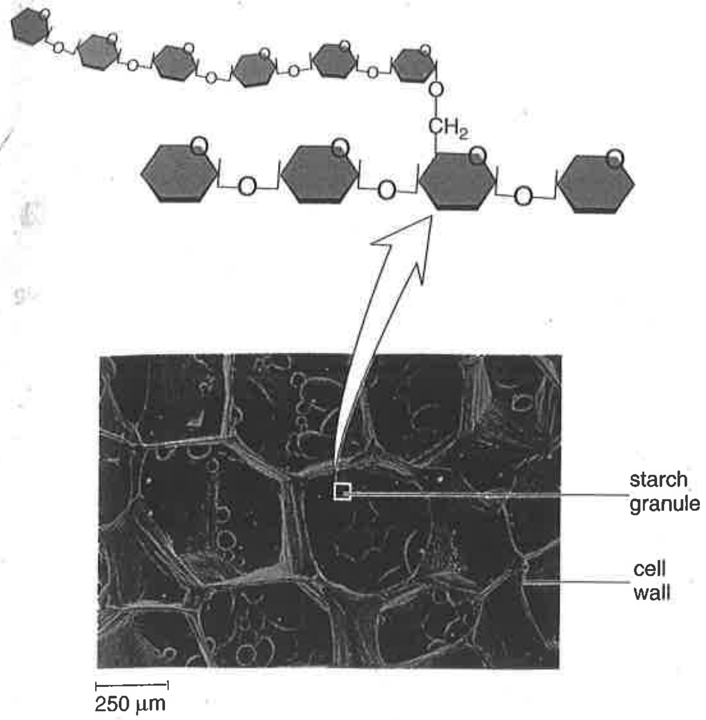


Figure 2.19 Starch structure and function.
Starch has straight chains of glucose molecules. Some chains are also branched as indicated. The electron micrograph shows starch granules in plant cells. Starch is the storage form of glucose in plants.

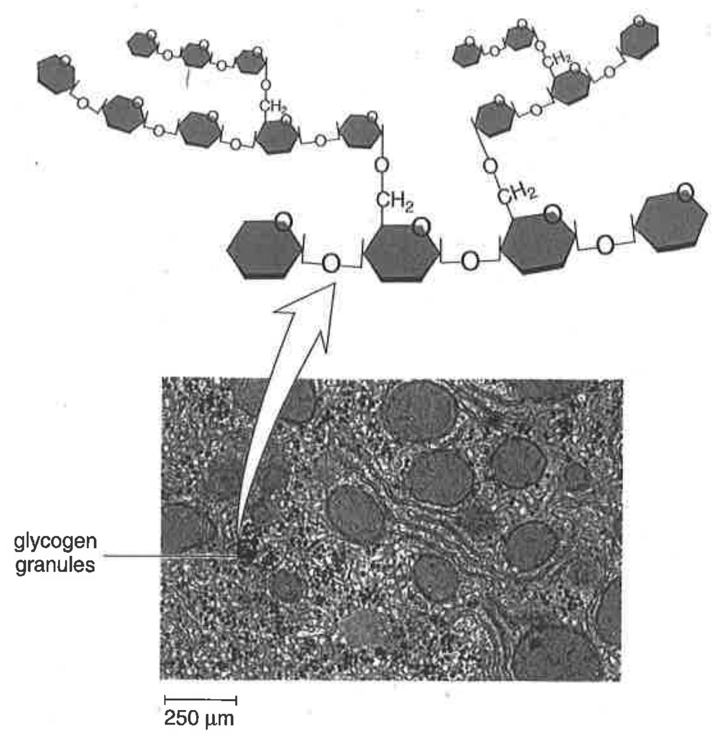


Figure 2.20 Glycogen structure and function.
Glycogen is a highly branched polymer of glucose molecules. The electron micrograph shows glycogen granules in liver cells. Glycogen is the storage form of glucose in animals.

After we eat starchy foods like bread, potatoes, and cake, glucose enters the bloodstream, and the liver stores glucose as glycogen. In between eating, the liver releases glucose so that the blood glucose concentration is always about 0.1%.

Cellulose

The polysaccharide **cellulose** is found in plant cell walls, and this accounts, in part, for the strong nature of these walls. In cellulose (Fig. 2.21), the glucose units are joined by a slightly different type of linkage than that in starch or glycogen. (Observe the alternating position of the oxygen atoms in the linked glucose units.) While this might seem to be a technicality, actually it is important because we are unable to digest foods containing this type of linkage; therefore, cellulose largely passes through our digestive tract as fiber, or roughage. Recently, it has been suggested that fiber in the diet is necessary to good health and may even help to prevent colon cancer.

Cells usually use the monosaccharide glucose as an energy source. The polysaccharides starch and glycogen are storage compounds in plant and animal cells, respectively, and the polysaccharide cellulose is found in plant cell walls.

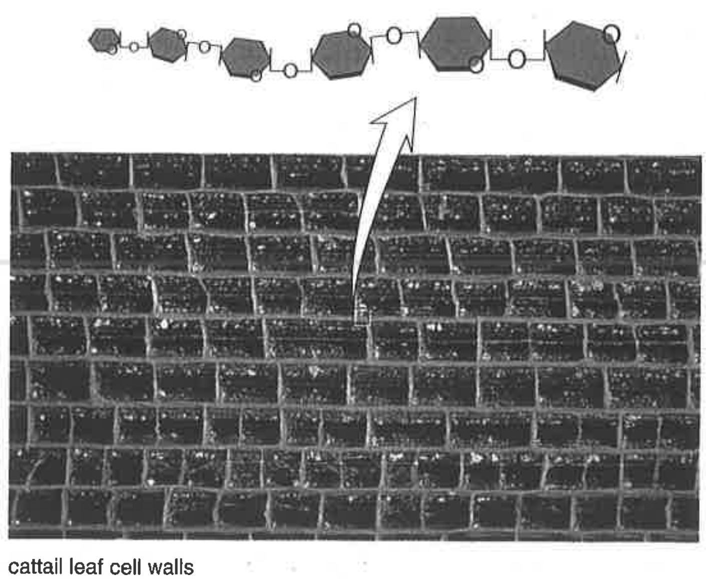


Figure 2.21 Cellulose structure and function.
Cellulose contains a slightly different type of linkage between glucose molecules than that in starch or glycogen. Plant cell walls contain cellulose, and the rigidity of the cell walls permits nonwoody plants to stand upright as long as they receive an adequate supply of water.

Visual Focus

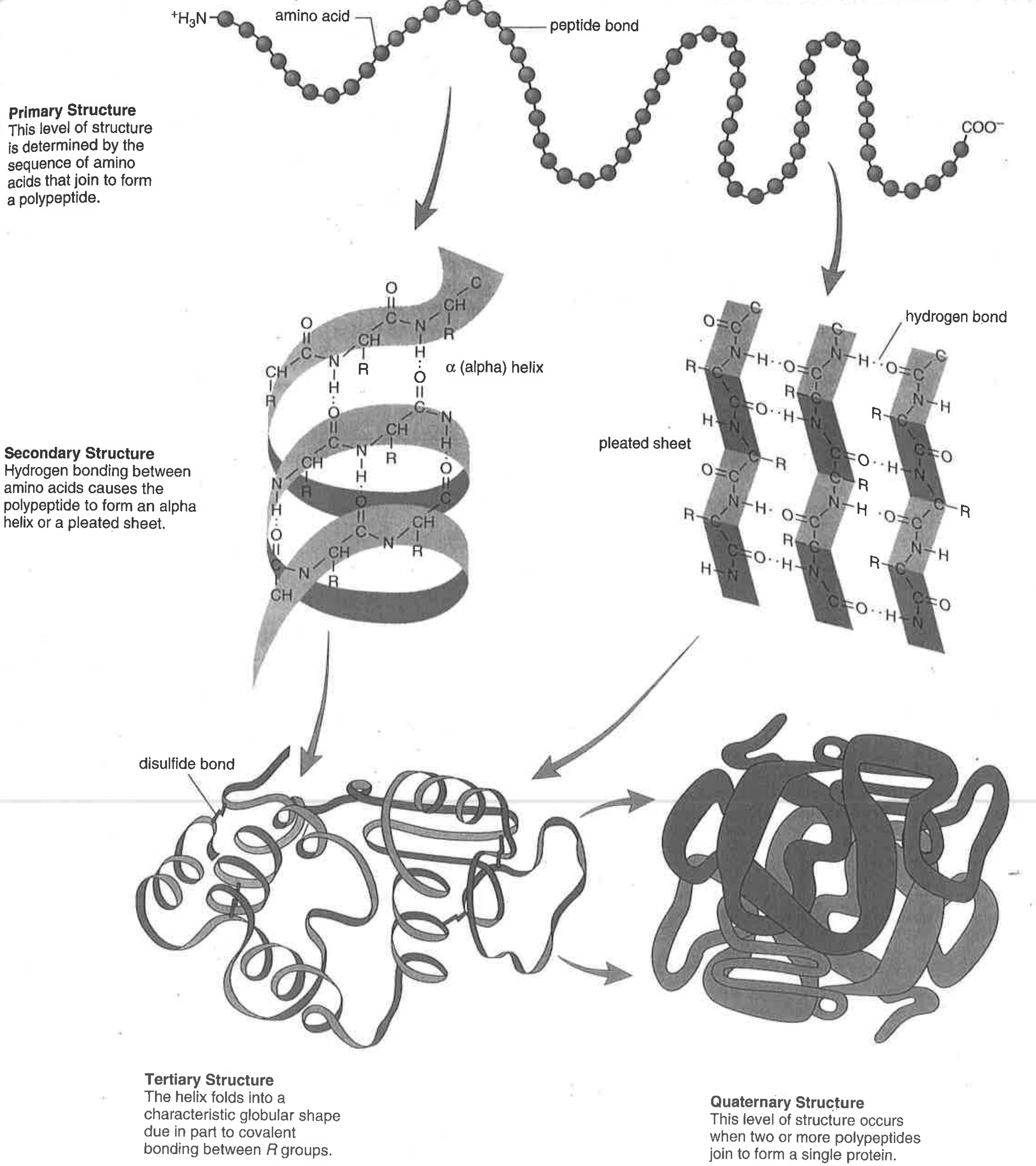


Figure 2.27 Levels of protein organization.

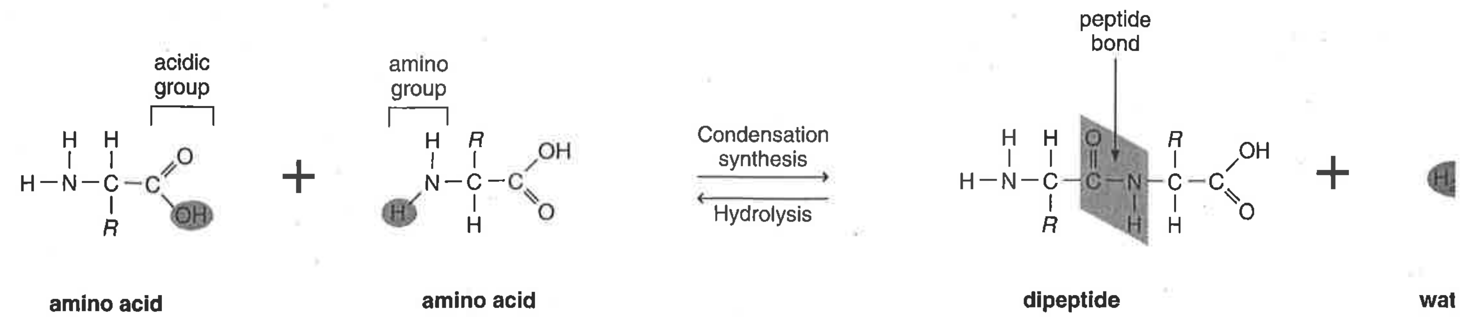
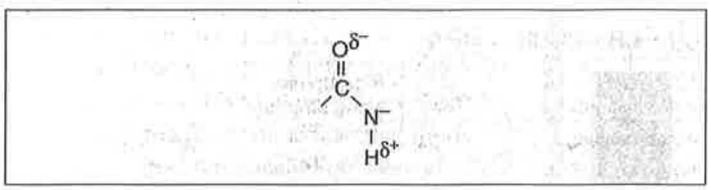


Figure 2.26 Condensation synthesis and hydrolysis of a dipeptide.
The two amino acids on the left-hand side of the equation differ by their *R* groups. As these amino acids join, a peptide bond forms, and a wate molecule is produced. During hydrolysis, water is added, and the peptide bond is broken.

Peptides

Figure 2.26 shows that a condensation synthesis reaction between two amino acids results in a dipeptide and a molecule of water. A bond that joins two amino acids is called a **peptide bond.** The atoms associated with a peptide bond—oxygen (O), carbon (C), nitrogen (N), and hydrogen (H)—share electrons in such a way that the oxygen has a partial negative charge and the hydrogen has a partial positive charge.



Therefore, the peptide bond is polar, and hydrogen bonding is possible between the C=O of one amino acid and the N—H of another amino acid in a polypeptide. A **polypeptide** is a single chain of amino acids.

Levels of Protein Organization

The structure of a protein has at least three levels of organization (Fig. 2.27*a–c*). The first level, called the *primary structure,* is the linear sequence of the amino acids joined by peptide bonds. Polypeptides can be quite different from one another. You will recall that the structure of a polysaccharide can be likened to a necklace that contains a single type "bead," namely, glucose. Polypeptides can make use of 20 different possible types of amino acids or "beads." Each particular polypeptide has its own sequence of amino acids. It can be said that each polypeptide differs by the sequence of its *R* groups and the number of amino acids in the sequence.

The *secondary structure* of a protein comes about when the polypeptide takes on a particular orientation in space. A coiling of the chain results in an alpha (α) helix, or a right-handed spiral, and a folding of the chain results in a pleated sheet. Hydrogen bonding between peptide bonds holds tl shape in place.

The *tertiary structure* of a protein is its final thre dimensional shape. In muscles, the helical chains myosin form a rod shape that ends in globular (glob shaped) heads. In enzymes, the helix bends and twists different ways. Invariably, the hydrophobic portions a packed mostly on the inside, and the hydrophilic portioı are on the outside where they can make contact with wate The tertiary shape of a polypeptide is maintained by vaı ous types of bonding between the *R* groups; covaler ionic, and hydrogen bonding all occur. One common for of covalent bonding between *R* groups is disulfide (S— linkages between two cysteine amino acids.

Some proteins have only one polypeptide, and son others have more than one polypeptide chain, each with i own primary, secondary, and tertiary structures. These se arate polypeptides are arranged to give some proteins fourth level of structure, termed the *quaternary structu* (Fig. 2.27*d*). Hemoglobin is a complex protein having quaternary structure; most enzymes also have a quate nary structure.

The final shape of a protein is very important to i function. As we will discuss in chapter 6, for example, e zymes cannot function unless they have their usual shap When proteins are exposed to extremes in heat and pl they undergo an irreversible change in shape called **den turation**. For example, we are all aware that the addition acid to milk causes curdling and that heating causes eg white, which contains a protein called albumin, to coag late. Denaturation occurs because the normal bonding b tween the *R* groups has been disturbed. Once a prote loses its normal shape, it is no longer able to perform i usual function.

Proteins, which contain covalently linked amino acids, are important in the structure and the function of cells. Some proteins are enzymes, which speed chemical reactions.

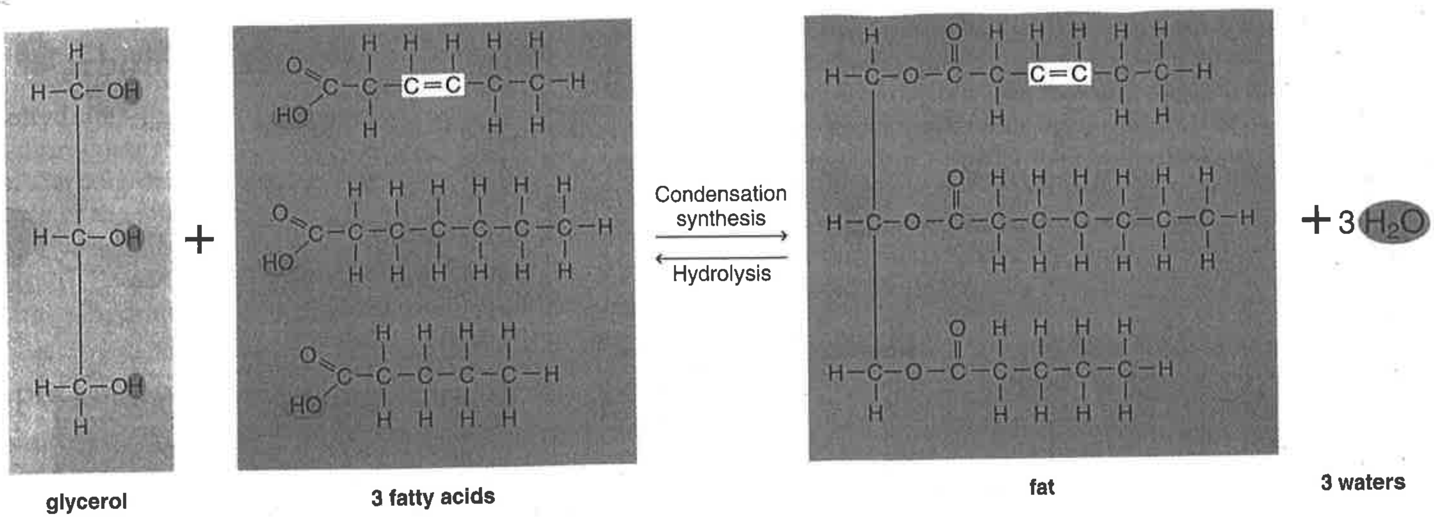


Figure 2.22 Condensation synthesis and hydrolysis of a fat molecule.
Fatty acids can be saturated (no double bonds between carbon atoms) or unsaturated (have double bonds, colored yellow, between carbon atoms). When a fat molecule forms, three fatty acids combine with glycerol, and three water molecules are produced.

2.6 Lipids

Lipids are diverse in structure and function, but they have a common characteristic: they do not dissolve in water.

Fats and Oils

The most familiar lipids are those found in fats and oils. **Fats,** which are usually of animal origin (e.g., lard and butter), are solid at room temperature. **Oils,** which are usually of plant origin (e.g., corn oil and soybean oil), are liquid at room temperature. Fat has several functions in the body: it is used for long-term energy storage, it insulates against heat loss, and it forms a protective cushion around major organs.

Fats and oils form when one glycerol molecule reacts with three fatty acid molecules. A fat is sometimes called a **triglyceride** because of its three-part structure, and the term neutral fat is sometimes used because the molecule is nonpolar (Fig. 2.22).

Saturated and Unsaturated Fatty Acids

A **fatty acid** is a hydrocarbon chain that ends with the acidic group —COOH (Fig. 2.22). Most of the fatty acids in cells contain 16 or 18 carbon atoms per molecule, although smaller ones with fewer carbons are also known.

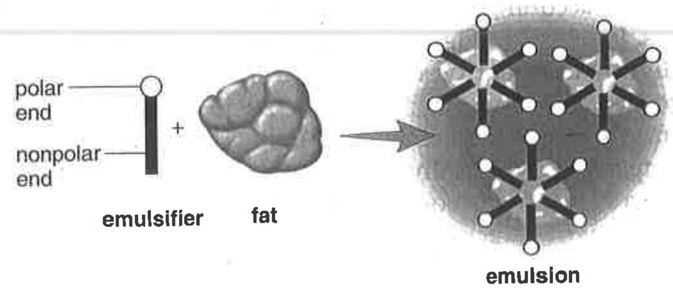
Fatty acids are either saturated or unsaturated. **Saturated fatty acids** have no double bonds between carbon atoms. The carbon chain is saturated, so to speak, with all the hydrogens it can hold. Saturated fatty acids account for the solid nature at room temperature of butter and lard, which are derived from animal sources. **Unsaturated fatty acids** have double bonds between carbon atoms wherever the number of hydrogens is less than two per carbon atom. Unsaturated fatty acids account for the liquid nature of vegetable oils at room temperature. Hydrogenation of vegetable oils can convert them to margarine and products such as Crisco.

Soaps

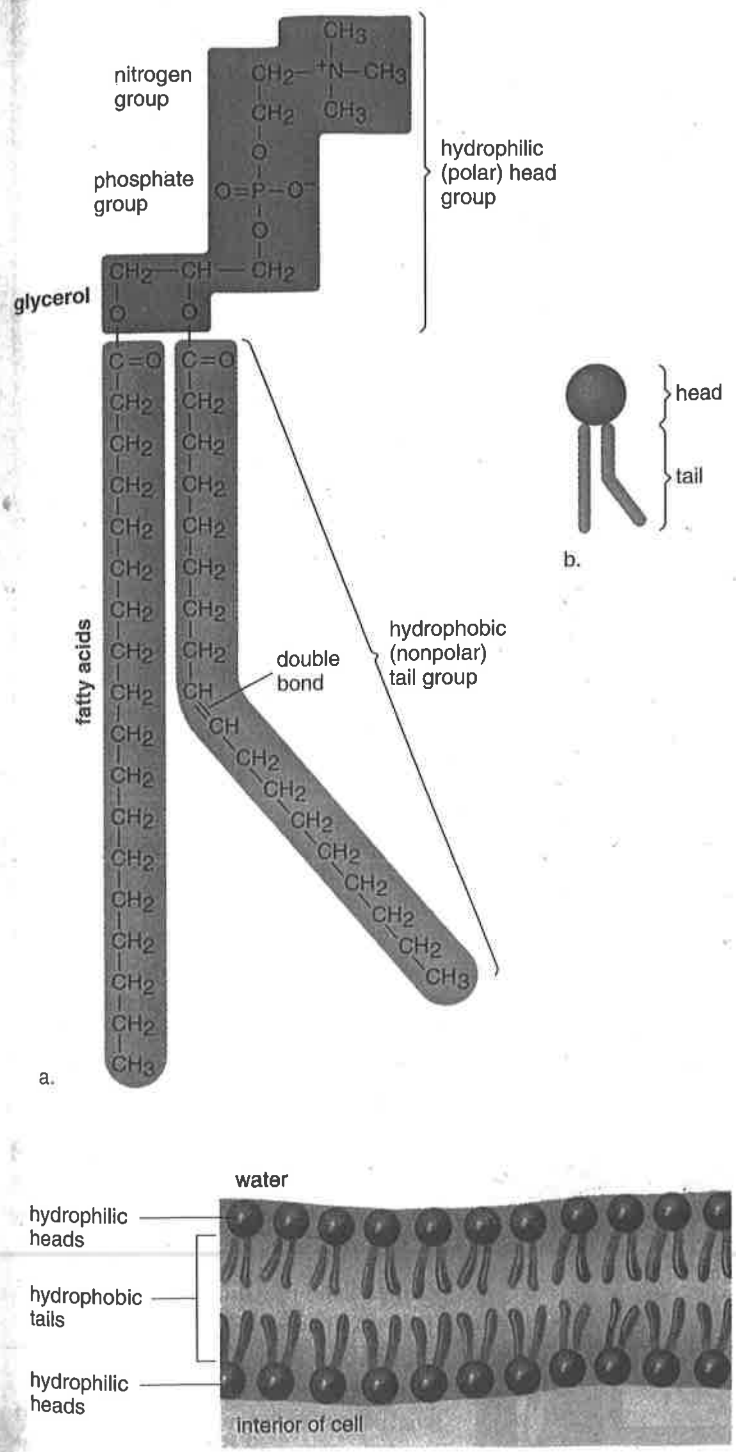
Strictly speaking, soaps are not lipids, but they are considered here as a matter of convenience. A **soap** is a salt formed from a fatty acid and an inorganic base. For example,

$$\underset{\text{sodium hydroxide}}{NaOH} + \underset{\text{fatty acid}}{RCOOH} \longrightarrow \underset{\text{soap}}{RCOO^- Na^+}$$

Unlike fats, soaps have a polar end that is hydrophilic in addition to the nonpolar end that is hydrophobic (the hydrocarbon chain represented by *R*). Therefore, a soap does mix with water. When soaps are added to oils, the oils, too, mix with water because a soap positions itself about an oil droplet so that its nonpolar ends project into the fat droplet while its polar ends project outward.



Now the droplet disperses in water, and it is said that **emulsification** has occurred. Emulsification occurs when dirty clothes are washed with soaps or detergents. Also, prior to the digestion of fatty foods, fats are emulsified by bile. A person who has had the gallbladder removed may have trouble digesting fatty foods because this organ stores bile for emulsifying fats prior to the digestion process.



c. **Phospholipid molecules in plasma membrane**

Figure 2.23 Phospholipid structure and shape.
a. Phospholipids are constructed like fats, except that they contain a phosphate group. This phospholipid also includes an organic group that contains nitrogen. **b.** The hydrophilic portion of the phospholipid molecule (head) is soluble in water, whereas the two hydrocarbon chains (tails) are not. **c.** This causes the molecule to arrange itself as shown when exposed to water.

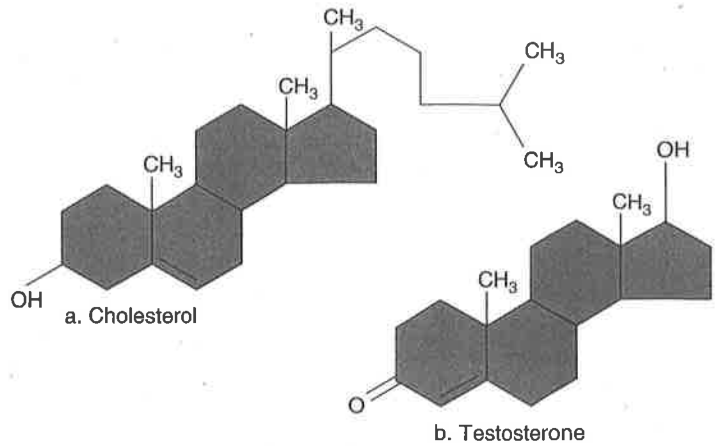


Figure 2.24 Steroid diversity.
a. Cholesterol, like all steroid molecules, has four adjacent rings, but the effects of steroids on the body largely depend on the attached groups indicated in red. **b.** Testosterone is the male sex hormone.

Phospholipids

Phospholipids, as their name implies, contain a phosphate group (Fig. 2.23). Essentially, they are constructed like fats, except that in place of the third fatty acid, there is a phosphate group or a grouping that contains both phosphate and nitrogen. These molecules are not electrically neutral as are fats because the phosphate and nitrogenous groups are ionized. It forms the so-called hydrophilic head of the molecule, while the rest of the molecule becomes the hydrophobic tails. The plasma membrane which surrounds cells is a phospholipid bilayer in which the heads face outward into a watery medium and the tails face each other because they are water repelling.

Steroids

Steroids are lipids having a structure that differs entirely from that of fats. Steroid molecules have a backbone of four fused carbon rings, but each one differs primarily by the arrangement of the atoms in the rings and the type of functional groups attached to them. Cholesterol is a component of an animal cell's plasma membrane and is the precursor of several other steroids, such as the sex hormones estrogen and testosterone (Fig. 2.24)

We know that a diet high in saturated fats and cholesterol can lead to circulatory disorders. This type of diet causes fatty material to accumulate inside the lining of blood vessels and blood flow is reduced. As discussed in the Science reading on page 36, nutrition labels are now required to list the calories from fat per serving and the percent daily value from saturated fat and cholesterol.

Lipids include fats and oils for long-term energy storage and steroids. Phospholipids, unlike other lipids, are soluble in water because they have a hydrophilic group.