CHEMICAL BONDS

Introduction

Living things are made up of atoms, but in most cases, those atoms aren't just floating around individually. Instead, they're usually interacting with other atoms (or groups of atoms).

For instance, atoms might be connected by strong bonds and organized into molecules or crystals. Or they might form temporary, weak bonds with other atoms that they bump into or brush up against. Both the strong bonds that hold molecules together and the weaker bonds that create temporary connections are essential to the chemistry of our bodies, and to the existence of life itself.

Why form chemical bonds? The basic answer is that atoms are trying to reach the most stable (lowest-energy) state that they can. Many atoms become stable when their valence shell is filled with electrons or when they satisfy the octet rule (by having eight valence electrons). If atoms don't have this arrangement, they'll "want" to reach it by gaining, losing, or sharing electrons via bonds.

Ions and ionic bonds

Some atoms become more stable by gaining or losing an entire electron (or several electrons). When they do so, atoms form **ions**, or charged particles. Electron gain or loss can give an atom a filled outermost electron shell and make it energetically more stable.

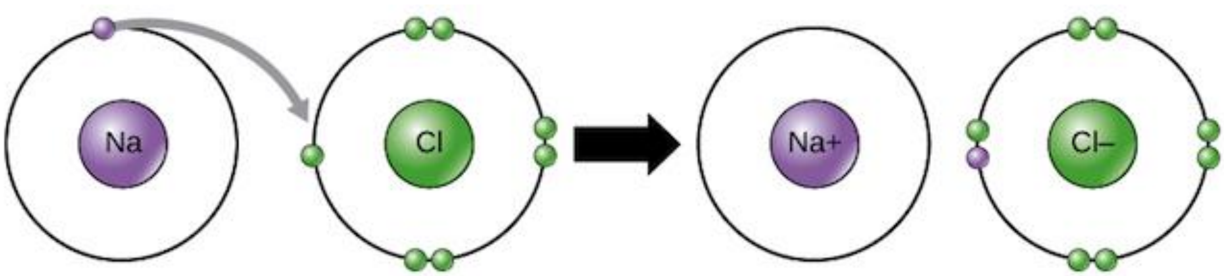
Forming ions

Ions come in two types. **Cations** are positive ions formed by losing electrons. For instance, a sodium atom loses an electron to become a sodium cation. Negative ions are formed by electron gain and are called **anions**. Anions are named using the ending "-ide": for example, the anion of chlorine is called chloride.

When one atom loses an electron and another atom gains that electron, the process is called **electron transfer**. Sodium and chlorine atoms provide a good example of electron transfer.

Sodium (Na) only has one electron in its outer electron shell, so it is easier (more energetically favorable) for sodium to donate that one electron than to find seven more electrons to fill the outer shell. Because of this, sodium tends to lose its one electron, forming Na^+.

Chlorine (Cl), on the other hand, has seven electrons in its outer shell. In this case, it is easier for chlorine to gain one electron than to lose seven, so it tends to take on an electron and become Cl^-.



Sodium transfers one of its valence electrons to chlorine, resulting in formation of a sodium ion (with no electrons in its 3n shell, meaning a full 2n shell) and a chloride ion (with eight electrons in its 3n shell, giving it a stable octet).

When sodium and chlorine are combined, sodium will donate its one electron to empty its shell, and chlorine will accept that electron to fill its shell. Both ions now satisfy the octet rule and have complete outermost shells. Because the number of electrons is no longer equal to the number of protons, each atom is now an ion and has a +1 Na^+ or –1 Cl^- charge.

In general, the loss of an electron by one atom and gain of an electron by another atom must happen at the same time: in order for a sodium atom to lose an electron, it needs to have a suitable recipient like a chlorine atom.

Making an ionic bond

Ionic bonds are bonds formed between ions with opposite charges. For instance, positively charged sodium ions and negatively charged chloride ions attract each other to make sodium chloride, or table salt. Table salt, like many ionic compounds, doesn't consist of just one sodium and one chloride ion; instead, it contains many ions arranged in a repeating, predictable 3D pattern (a crystal).

Certain ions are referred to in physiology as **electrolytes** (including sodium, potassium, and calcium). These ions are necessary for nerve impulse conduction, muscle contractions and water balance. Many sports drinks and dietary supplements provide these ions to replace those lost from the body via sweating during exercise.

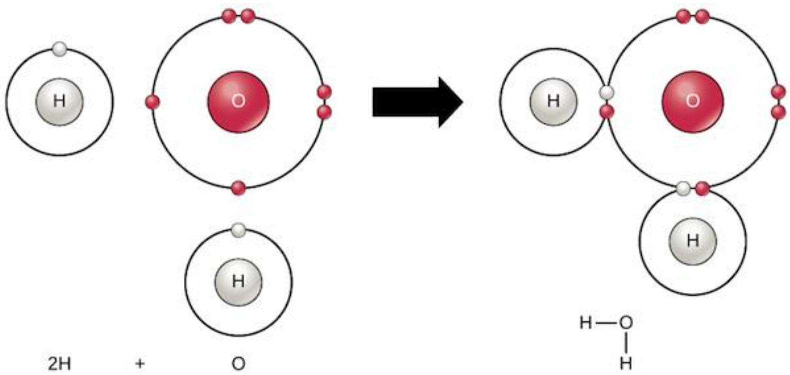
Covalent bonds

Another way atoms can become more stable is by sharing electrons (rather than fully gaining or losing them), thus forming **covalent bonds**.

Covalent bonds are more common than ionic bonds in the molecules of living organisms.

For instance, covalent bonds are key to the structure of carbon-based organic molecules like our DNA and proteins. Covalent bonds are also found in smaller inorganic molecules, such as H2O, O2 and CO2. One, two, or three pairs of electrons may be shared between atoms, resulting in single, double, or triple bonds, respectively. The more electrons that are shared between two atoms, the stronger their bond will be.

As an example of covalent bonding, let's look at water. A single water molecule consists of two hydrogen atoms bonded to one oxygen atom. Each hydrogen shares an electron with oxygen, and oxygen shares one of its electrons with each hydrogen:



Hydrogen atoms sharing electrons with an oxygen atom to form covalent bonds, creating a water molecule

The shared electrons split their time between the valence shells of the hydrogen and oxygen atoms, giving each atom something resembling a complete valence shell (two electrons for H, eight for O). This makes a water molecule much more stable than its component atoms would have been on their own.

Polar covalent bonds

There are two basic types of covalent bonds: polar and nonpolar. In a **polar covalent bond**, the electrons are unequally shared by the atoms and spend more time close to one atom than the other. Because of the unequal distribution of electrons between the atoms of different elements, slightly positive (δ+) and slightly negative (δ–) charges develop in different parts of the molecule.

In a water molecule (above), the bond connecting the oxygen to each hydrogen is a polar bond. Oxygen is a much more **electronegative** atom than hydrogen, meaning that it attracts shared electrons more strongly, so the oxygen of water bears a partial negative charge (has high electron density), while the hydrogens bear partial positive charges (have low electron density).

In general, the relative electronegativities of the two atoms in a bond – that is, their tendencies to "hog" shared electrons – will determine whether a covalent bond is polar or nonpolar. Whenever one element is significantly more electronegative than the other, the bond between them will be polar, meaning that one end of it will have a slight positive charge and the other a slight negative charge.

Nonpolar covalent bonds

Nonpolar covalent bonds form between two atoms of the same element, or between atoms of different elements that share electrons more or less equally. For example, molecular oxygen O_2 is nonpolar because the electrons are equally shared between the two oxygen atoms.

Another example of a nonpolar covalent bond is found in CH_4. Carbon has four electrons in its outermost shell and needs four more to achieve a stable octet. It gets these by sharing electrons with four hydrogen atoms, each of which provides a single electron. Reciprocally, the hydrogen atoms each need one additional electron to fill their outermost shell, which they receive in the form of shared electrons from carbon. Although carbon and hydrogen do not have exactly the same electronegativity, they are quite similar, so carbon-hydrogen bonds are considered nonpolar.

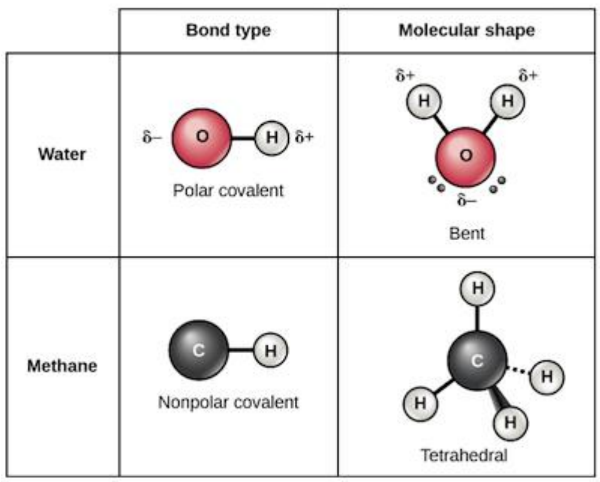


Table showing water and methane as examples of molecules with polar and nonpolar bonds, respectively

Hydrogen bonds and London dispersion forces

Covalent and ionic bonds are both typically considered strong bonds. However, other kinds of more temporary bonds can also form between atoms or molecules. Two types of weak bonds often seen in biology are hydrogen bonds and London dispersion forces.

Not to be overly dramatic, but without these two types of bonds, life as we know it would not exist! For instance, hydrogen bonds provide many of the life-sustaining properties of water and stabilize the structures of proteins and DNA, both key ingredients of cells.

Hydrogen bonds

In a polar covalent bond containing hydrogen (e.g., an O-H bond in a water molecule), the hydrogen will have a slight positive charge because the bond electrons are pulled more strongly toward the other element. Because of this slight positive charge, the hydrogen will be attracted to any neighboring negative charges. This interaction is called a **hydrogen bond**.

Hydrogen bonds are common, and water molecules in particular form lots of them. Individual hydrogen bonds are weak and easily broken, but many hydrogen bonds together can be very strong.

London dispersion forces

Like hydrogen bonds, **London dispersion forces** are weak attractions between molecules. However, unlike hydrogen bonds, they can occur between atoms or molecules of any kind, and they depend on temporary imbalances in electron distribution.

How does that work? Because electrons are in constant motion, there will be some moments when the electrons of an atom or molecule are clustered together, creating a partial negative charge in one part of the molecule (and a partial positive charge in another). If a molecule with this kind of charge imbalance is very close to another molecule, it can cause a similar charge redistribution in the second molecule, and the temporary positive and negative charges of the two molecules will attract each other.

Hydrogen bonds and London dispersion forces are both examples of **van der Waals forces**, a general term for intermolecular interactions that do not involve covalent bonds or ions.^3[3]cubed Some textbooks use the term "van der Waals forces" to refer only to London dispersion forces, so make sure you know what definition your textbook or teacher is using.

How does that work in a cell?

Both strong and weak bonds play key roles in the chemistry of our cells and bodies. For instance, strong covalent bonds hold together the chemical building blocks that make up a strand of DNA. However, weaker hydrogen bonds hold together the two strands of the DNA double helix. These weak bonds keep the DNA stable, but also allow it to be opened up for copying and use by the cell.

More generally, bonds between ions, water molecules, and polar molecules are constantly forming and breaking in the watery environment of a cell. In this setting, molecules of different types can and will interact with each other via weak, charge-based attractions. For instance, a Na^+ ion might interact with a water molecule in one moment, and with the negatively charged part of a protein in the next moment.

INTRODUCTION TO MACROMOLECULES

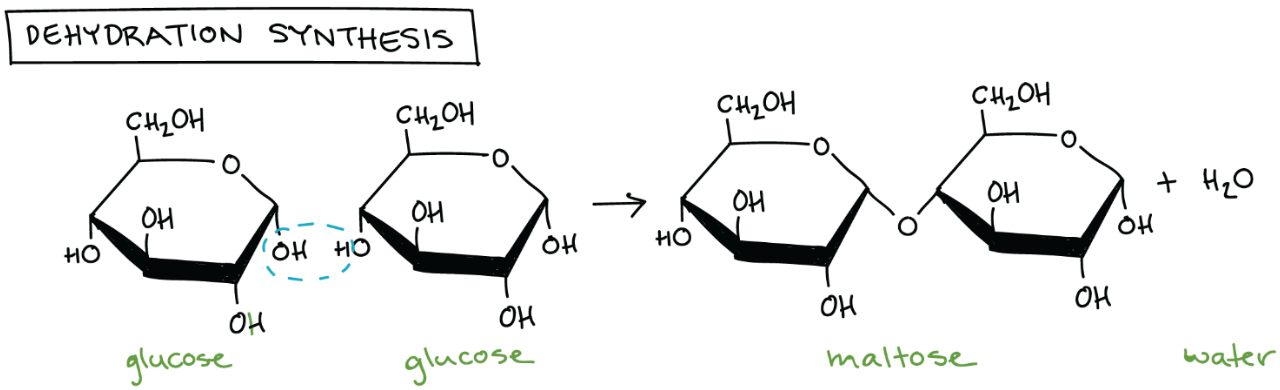
Monomers and polymers

Most large biological molecules are **polymers**, long chains made up of repeating molecular subunits, or building blocks, called **monomers**. If you think of a monomer as being like a bead, then you can think of a polymer as being like a necklace, a series of beads strung together.

Carbohydrates, nucleic acids, and proteins are often found as long polymers in nature. Because of their polymeric nature and their large (sometimes huge!) size, they are classified as **macromolecules**, big (*macro*-) molecules made through the joining of smaller subunits. Lipids are not usually polymers and are smaller than the other three, so they are not considered macromolecules by some sources^{1,2}[1,2]start superscript, 1, comma, 2, end superscript. However, many other sources use the term “macromolecule” more loosely, as a general name for the four types of large biological molecules^{3,4}[3,4]start superscript, 3, comma, 4, end superscript. This is just a naming difference, so don’t get too hung up on it. Just remember that lipids are one of the four main types of large biological molecules, but that they don’t generally form polymers.

Dehydration synthesis

How do you build polymers from monomers? Large biological molecules often assemble via **dehydration synthesis** reactions, in which one monomer forms a covalent bond to another monomer (or growing chain of monomers), releasing a water molecule in the process. You can remember what happens by the name of the reaction: dehydration, for the loss of the water molecule, and synthesis, for the formation of a new bond.



Dehydration synthesis reaction between two molecules of glucose, forming a molecule of maltose with the release of a water molecule.

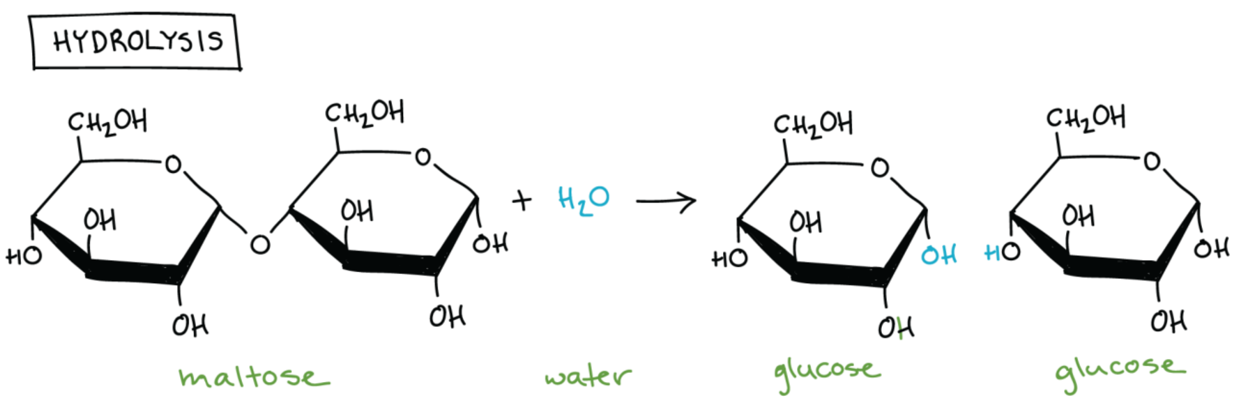
In the dehydration synthesis reaction above, two molecules of the sugar glucose (monomers) combine to form a single molecule of the sugar maltose. One of the glucose molecules loses an H, the other loses an OH group, and a water molecule is released as a new covalent bond forms between the two glucose molecules. As additional monomers join by the same process, the chain can get longer and longer and form a polymer.

Even though polymers are made out of repeating monomer units, there is lots of room for variety in their shape and composition. Carbohydrates, nucleic acids, and proteins can all contain multiple different types of monomers, and their composition and sequence is important to their function. For instance, there are four types of nucleotide monomers in your DNA, as well as twenty types of amino acid monomers commonly found in the proteins of your body. Even a single type of monomer may form different polymers with different properties. For example, starch, glycogen, and cellulose are all carbohydrates made up of glucose monomers, but they have different bonding and branching patterns.

Hydrolysis

How do polymers turn back into monomers (for instance, when the body needs to recycle one molecule to build a different one)? Polymers are broken down into monomers via **hydrolysis** reactions, in which a bond is broken, or lysed, by addition of a water molecule.

During a hydrolysis reaction, a molecule composed of multiple subunits is split in two: one of the new molecules gains a hydrogen atom, while the other gains a hydroxyl (-OH) group, both of which are donated by water. This is the reverse of a dehydration synthesis reaction, and it releases a monomer that can be used in building a new polymer. For example, in the hydrolysis reaction below, a water molecule splits maltose to release two glucose monomers. This reaction is the reverse of the dehydration synthesis reaction shown above.



Hydrolysis of maltose, in which a molecule of maltose combines with a molecule of water, resulting in the formation of two glucose monomers.

Dehydration synthesis reactions build molecules up and generally require energy, while hydrolysis reactions break molecules down and generally release energy. Carbohydrates, proteins, and nucleic acids are built up and broken down via these types of reactions, although the monomers involved are different in each case. (In a cell, nucleic acids actually aren't polymerized via dehydration synthesis; we'll examine how they're assembled in the article on nucleic acids. Dehydration synthesis reactions are also involved in the assembly of certain types of lipids, even though the lipids are not polymers.

In the body, enzymes catalyze, or speed up, both the dehydration synthesis and hydrolysis reactions. Enzymes involved in breaking bonds are often given names that end with -*ase*: for instance, the maltase enzyme breaks down maltose, lipases break down lipids, and peptidases break down proteins (also known as polypeptides, as we'll see in the article on proteins). As food travels through your digestive system – in fact, from the moment it hits your saliva – it is being worked over by enzymes like these. The enzymes break down large biological molecules, releasing the smaller building blocks that can be readily absorbed and used by the body.