Chapter 3

Chemistry

I am often amazed at the bad advice that colleges give to their new students. The number one piece of awful advice is that you don't need chemistry before you take Human A&P. Poppycock! The whole body is made of chemicals! In Human A&P, you will be studying enzymes. These regulate chemical reactions. You will be studying ATP; this provides energy for chemical reactions. You will be studying diffusion, which is the motion of molecules. You will be studying the pH of solutions, salinity, ionic equilibria, hydrogen bonds... all kinds of things that are really just chemistry. In fact, it was the importance of chemistry that inspired me to write this book.

So, if you're floundering, it may be that you just need to review your chemistry. You'll be amazed at how much it helps. Read on!

3.1 The Atom

Most chemistry courses start with the history of chemistry and the earliest chemists: Avagadro, Lavoisier, Boyle, Hooke, and several others. It is fascinating stuff, but we just don't have time before your next test. Suffice it to say that by carefully burning things, compressing air and weighing chemicals, these men were able to determine that there are atoms, and that everything we know of is made of them. Eventually, a connection was made between the concept of the atom, and the weird effects of electricity, and our modern notion of subatomic particles was discovered.

An atom is a combination of two or three kinds of particles: the ELECTRON, the PROTON, and the NEUTRON. Protons and neutrons are much heavier than electrons, and these heavy particles stick to each other in the center of the atom. This clump of protons and neutrons is called the nucleus. Surrounding the nucleus, we have the tiny electrons whizzing around so fast that nobody can tell where they are exactly. Nevertheless, the electrons tend to be roughly organized into regions around the nucleus called shells and orbitals. They sort of form layers.

Electrons are attracted to protons because they have opposite electrical charges. The electron has a charge of -1 and a proton has a charge of +1. This attraction keeps the electrons around the nucleus, but for some reason they don't usually actually crash into the protons. The amount of force that the nucleus exerts on the electrons depends on lots of factors, but mainly on the number of protons and the way that the other electrons in their various shells and orbitals cause interference. Electrons like to sit in neatly arranged shells and orbitals, and they particularly like to fill them up. It's as if you had a magic box of eggs. If you take one egg out, another gets pulled in from somewhere, just to fill up the dozen pockets. Now imagine a stack of these egg cartons. The top one likes to be either full or empty, but the ones underneath never get disturbed. Electrons fill their shells in the same way, regardless of the number of protons. Another way to say the same thing is that a full shell is stable.

Now, the number of protons in an atom will affect how hard it is to pull an electron away and what over-all charge you have when it is gone. The over-all charge of an atom is simply the number of protons minus the number of electrons. A neutral atom (which has as many protons as neutrons) is not strongly attracted to other atoms. But because of the egg-carton effect, a neutral atom wih a partly full shell will be very reactive. It will either drop its excess electrons, or grab electrons from other atoms. On the other hand, an atom with a charge (called an ion) may be very stable and non-reactive, if its outer shell of electrons is either full or completely empty.

One more thing: what about those neutrons? Don't they do anything? Yes and no. They won't have any effect on any chemical reaction, but they do have mass, and they help to hold the nucleus together. The mass of an atom depends almost entirely on the number of protons and neutrons; electrons have almost no mass. A proton is about as heavy as a neutron. For our purposes, one proton-mass equals one neutron-mass, equals one Atomic Mass Unit (or "Dalton"). If you change the number of neutrons, you change the mass of the atom, and you might cause the nucleus itself to split into two different kinds of atoms. This is where things like atomic power and radioactivity come from, but it isn't directly relevant to how living bodies work: most of the nuclei in our body are stable.

3.2 The Table of Elements

Because the number of protons determines how the electrons behave, each atom with the same number of protons behaves in the same way. We say that they are the same ELEMENT. Some elements you may be familiar with are iron, oxygen, hydrogen, nitrogen, carbon, aluminum, and chlorine. There are over a hundred others. Elements combine in different ways to form COMPOUNDS such as water, ammonia, sugars, and salt. It would be impossible to count all the possible different compounds, which is why the universe is so complex and interesting.

Long ago, scientists noticed that although each element has unique properties, some of them seem to behave similarly. They form families, of a sort. Eventually, by studying these families and the masses of their atoms and so forth, they realized that the similarities came from having similar numbers of electrons in the outer shell of the atom. So, they arranged the elements in a table that reflected the increasing number of protons and the increasing size of each electron shell. The first shell contains two electrons, the second contains eight, the third another eight, the fourth 18, and so on. The table is called the Periodic Table of Elements.

The first element is hydrogen. It has one proton, and easily loses its one electron so that its outer shell is empty. The second element is helium. It has two protons and two electrons. Because its outer shell is full, helium does not need to lose or gain any electrons. It is very stable in the neutral state, and we call it *inert*. It does not enter into any chemical reactions. Hydrogen and helium form the first row of the Periodic Table.

The second row of the table consists of: lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine and neon, in that order. Like hydrogen, lithium really wants to lose that one electron in its outer shell. Like helium, neon is inert because its outer shell is already full. Fluorine really wants to *grab* one more electrons. Carbon and nitrogen, because they are in the middle, don't want to gain or lose electrons, but they do want to share them. More on that in the next section. I won't go through the entire table, but we should look at two other very important elements before moving on: sodium and chlorine. Sodium's chemical symbol is Na. It sits right under lithium in the Periodic Table. So, it also has just one electron in its outer shell, and it is just fine getting rid of it. You will see a lot of sodium in Human A&P, and it will always be in the form of a +1 ion, so it will usually be written Na^+, and it almost never grabs any electrons. It is very stable just the way it is.

At the other end of the same row is chlorine (Cl). Because it is just one electron short of a full shell, it really wants to grab one to become a chloride ion, Cl^-. This is also very stable. Guess what happens when neutral sodium meets neutral chlorine? Sodium gives chlorine an electron, and then the two oppositely charged ions stick to each other! Actually, what you get is a big 3-dimensional grid of ions in which the sodium ions and chloride ions alternate, with each sodium attracted to all the chlorines around it, and vice-versa. By the way, just below sodium on the periodic table is potassium (K), which behaves in very much the same way. It likes to exist as K^+.

As the table of elements continues on, things get a little weirder, because the shells get so big and the electrons start interfering with each other. This means that we get more subtle differences between the heavier elements, and they start to appear in multiple forms. Iron, for example, can exist in a +1, +2 or +3 form, which is important in understanding hemoglobin.

In the Periodic Table, each of these elements is represented by a one- or two-letter symbol, such as H or K or Fe. A one-letter symbol is always uppercase, and in a two-letter symbol, the first letter is always capitalized and the second is always lower case; this avoids confusion. Here are the symbols of some useful elements:

3.3 Compounds, Molecules and Covalent Bonds

We've already seen one compound, salt. It's written NaCl, for "sodium chloride." Water is another compound, and most people know that it is written H_2O, meaning one oxygen atom and two hydrogen atoms in each MOLECULE. A number following a chemical symbol indicates how many of that atom is in the molecule. There is a big difference between water and salt, however. Salt does not have molecules, really. A molecule is a discrete (separate) clump of atoms that are bound to each other by *sharing* their electrons. Salt has lots of ions all arranged in a regular array, like we've seen. No two of the ions are stuck to each other more than to the other ions around them. And the ions don't share; the chloride takes and the sodium gives.

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Table 3.1: A few of the more common elements

Symbol	Element	Comments about the pure, neutral state
H	Hydrogen	A colorless, “diatomic” gas: H_2
O	Oxygen	A colorless, “diatomic” gas: O_2
N	Nitrogen	A colorless, “diatomic” gas: N_2
C	Carbon	A black, powdery solid
Na	Sodium (the Latin name is *Natrium*)	A soft metal. Reacts violently in water to form
K	Potassium (the Latin name is *Kalium*)	NaĀ.soft metal. Reacts violently in water to form K^+.
Cl	Chlorine	A green, poisonous “diatomic” gas: Cl_2
P	Phosphorus	A powdery or waxy solid.
Fe	Iron (the Latin name is *Ferrum*)	A hard, dull gray metal
S	Sulfur	A yellow powdery solid.

In a true molecule, like water, the atoms are still trying to fill up their outer shells, but there is a problem: the atoms are too similar, so they can’t “decide” who gets to keep the electrons. Instead, they share electrons in what are called “molecular orbitals.” In the case of water, the oxygen needs two more electrons to finish its outer shell. Hydrogen often wants to lose its single electron, but notice that it would also have a full shell if it gains one. So, if the oxygen shares an electron with each hydrogen, and each hydrogen shares an electron with the oxygen, they can kind of pretend that they have full shells. This kind of bond, in which two atoms share a pair of electrons, is called a COVALENT BOND. A molecule of water has two covalent bonds; each is between the oxygen and one of the hydrogens. Notice that there are no ions here, no total loss or gain of electrons. However, the oxygen is a little greedy. Oxygen attracts the electrons a little more strongly than hydrogen does, so the hydrogens are a little bit positive, and the oxygen is a little bit negative. We will come back to this later, because it turns out to be very important when we study water more deeply.

By the way, sometimes there are *two* covalent bonds between the same two atoms; they are called double bonds.

Finally, there are some molecules that have a charge, or if you prefer, ions that are made of multiple atoms, tied together with covalent bonds. Sulfate, nitrate and phosphate are three common examples. Sulfate is the SO_4^{2-} ion. Nitrate is the NO_3^- ion. Phosphate is the PO_4^{3-} ion. Each of these ions has atoms that are covalently bonded to each other, so they tend not to break apart in chemical reactions. But, they all have a negative charge, so they will be attracted to positive ions. For example, phosphate can attract three hydrogen ions (H^+) to form phosphoric acid (H_3PO_4). Any positively charged ion could also be attracted to it. For example a phosphate and three sodium ions forms sodium phosphate, Na_3PO_4.

3.4 Chemical Equations

When I was in highschool, it took forever for me to realize that a chemical “equation” has almost nothing to do with algebraic equations. An algebraic equation is a statement that the two sides have the same value. A chemical equation is a *process* in which both sides contain all the same atoms. For example, 2H $\rightarrow$ H2 means that two individual atoms of hydrogen will react to form a diatomic (two of the same atom) molecule, which is called hydrogen gas. Another example: glucose is the sugar that our body burns; its formula is $C_6H_{12}O_6$. When it combines with oxygen, we get:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

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The arrow means something like, "makes" not "equals." This formula could be read, "one glucose molecule will react with six oxygen molecules to make six carbon-dioxide molecules and six water molecules."

Sometimes, we have chemical equations that are *reversible.* That means that the stuff on one side can turn into the stuff on the other side, but some of it is always turning back. So, really we have both sides present at the same time. When this happens, we use a "$\rightleftharpoons$" double-arrow instead of the "$\rightarrow$."

3.5 Energy and Bonds

We've been talking about matter so far, but now we need to talk about energy. MATTER is stuff that you can feel. It takes up room and it has mass. ENERGY is a bit more abstract; it is the "potential to do work." It might be easier to think of it as the ability to cause change. If a rock is sitting still, you need energy to get it to move. If you have two atoms that are bound to each other, you need energy to break them apart. Some forms of energy include:

- Gravitational Potential Energy: the energy that gravity imparts to matter when it pulls it.
- Kinetic Energy: the energy that a moving thing has. It can cause change in an object when one thing crashes into another thing.
- Sound Energy: this is a wave of energy that is caused by vibrating matter. It is just like the waves that spread out in a pond when you drop a rock in the middle. The water waves can make a boat bob up and down. Sound energy can make another piece of matter vibrate.
- Light Energy: This is another wave, but it is caused by the motion of charged particles, such as electrons and protons. When light hits an electron, the electron gets some energy and gets elevated to a higher orbital. If it gets enough energy, it might even fly off. When an electron falls back down to a lower level, it gives off another particle of light (called a *photon*). You might guess that light can affect some chemical reactions, and you'd be right.
- Heat Energy: This is actually the kinetic energy of individual atoms and molecules. Atoms and molecules are always in motion. Sometimes they are whizzing around like so many bees in a swarm. Sometimes they just sort of twitch in place. Often, the individual atoms in a molecule are also moving relative to each other, like one of those ball-and-paddle toys with the rubber band, or like the parts of a mobile, hanging on a string. The faster and the more different ways they are moving, the more heat they have. Chemical reactions can happen when atoms crash into each other hard enough, so you can imagine that heat is important in chemistry. Temperature, by the way, is the *average* kinetic energy of all the atoms in a body of matter.

As you can see, there are many kinds of energy that are associated with chemistry. In fact, whenever a chemical bond is made, the molecule gives off energy (in the form of heat and light), and energy is needed to break any chemical bond.

Now, it is important to understand some basic laws of energy and how it works. These are summarized in the THREE LAWS OF THERMODYNAMICS.

1. The First Law: Energy can not be created or destroyed. It can only be transferred or transformed. For example, when you drop an object, the gravitational potential energy gets turned into kinetic energy as the object speeds toward the ground.
2. The Second Law is very complex. Chemists have at least three different ways to state it, and they each look very different, while basically meaning the same thing.
   (a) The easiest to understand is "Energy flows 'down hill,"' that is, energy only moves from where there is more energy to where there is less. Heat does not flow spontaneously from something cold to something hot. This is why your hand gets warm, not cold, when you hold a hot cup of coffee.
   (b) The second way to state the Second Law is that there is always some inefficiency when energy is transfered or transformed. The "lost" energy usually becomes heat.
   (c) The form of the Second Law that is most difficult to understand has to do with something called *entropy.* Entropy is randomness or disorder. It has to do with the distribution of energy, or matter, not the quantity. If all the matter or energy is concentrated in one place then there is low entropy (or high

order). If it is distributed evenly across the space, then there is high entropy. Stated in these terms, the Second Law says that the entropy of a closed system (a volume of space in which no matter or energy can enter or leave) is always increasing – although it stops when the distribution of energy is completely uniform. This concept is more difficult to understand than the first two versions of the law, but it encompasses both of them and is extremely useful.

3. The Third Law: There is a minimum possible temperature, called absolute zero, and it is impossible for anything to actually get there. If we count up from absolute zero, using Celsius degrees, we are using the Kelvin scale of temperature. On this scale, the freezing point of water is 273.15 K (notice that the Kelvin scale does not use the little circle, just a K). The boiling point is 373.15 K.

These laws together mean that chemical reactions can only occur when there is energy to drive them, or when the gain in entropy would be great. For reactions in our body, that energy comes from the food we eat, and ultimately from the energy of the sun. They also mean that the chemicals in our cells are always breaking down, and we need energy to repair them. The energy in chemical bonds is used to drive these processes.

3.6 Catalysts

A chemical reaction can only happen when there is enough energy to drive it. But nearly all chemical reactions also need a little "push" to get them going. We call this push the ENERGY OF ACTIVATION. The reaction is like a golf ball on field. If the field is sloped, the ball will roll downward. But if the ball gets caught in a little pocket in the ground – a hole or a shallow depression – it may stop rolling. Then you have to knock it out with your club. Just a little tap might get it going again, or you might have to whack it. If you get it to the lip of the little depression, the ball will roll all the way down hill. This extra little required push means that many compounds are stable in the body, even if they do have enough energy to react. Or, to put it another way, the reaction may proceed, but only v-e-r-y slowly – every now and then a little push will come along by accident. In the body, these reactions may be so slow that they appear not to occur at all.

A CATALYST is something that speeds up a reaction without itself getting used up. It's not a source of energy, so much as a tunnel that makes it easier for our ball to roll through a barrier. One way for a catalyst to do this is to hold the molecules in just the right position so that little energy is needed to get them to react. Another way is for the catalyst to borrow energy from somewhere and then pay it back.

Because there are many very slow reactions in the body, catalysts can be used as switches or gates. When a catalyst is present, the reaction proceeds, but when it is absent, it stops almost completely. Catalysts in the body are called enzymes, and they have the amazing property of being highly specific. A catalyst for one reaction will not affect a different one nearby. This is very useful for keeping order in the cell.

3.7 Solids, Liquids and Gasses, the Phases of Matter

In addition to the bonds that hold atoms together in a molecule, there are also weaker bonds that hold molecules together. There are many kinds. But as matter gets hotter, these bonds can be overcome, and the molecules can go their separate ways. This heat causes solids to turn to liquids, and liquids to turn to gasses.

Let's start with some definitions. A SOLID is a body of matter that can hold its own shape without support by its container. You can pop an ice cube out of an ice-cube tray, and it will retain its cube-shape on a plate or in a glass. A LIQUID is a body of matter that takes the shape of the bottom of its container. If you let the ice cube sit at the bottom of a glass, it will eventually melt, and it will fill the bottom of the glass. A GAS is a body of matter that expands to fill its container. If you put that ice cube in a metal bottle and heat it to the boiling point, it will turn into steam, and the steam will fill the whole bottle (it might also explode, so don't try this at home!).

When matter changes state, something odd happens. Normally, if you add heat to some matter, the temperature goes up – this is the way we are used to thinking of things. But when you have added enough heat, the energy does something different: instead of speeding up the vibration of a molecule, it breaks the bonds between the molecules. Because the vibrational speed is not increasing, the temperature is not going up. This is not just a technicality: you can measure it! Take a bunch of ice cubes in a bowl and put a thermometer in it. As it melts, stir it to make sure the temperature is the same throughout the bowl. Once the ice cubes start melting, the temperature will stop going up, and it will stay the same until the ice is all melted. At that point it will start going up again. Meanwhile, the temperature outside the bowl will keep going down the whole time. The heat from outside the bowl is going

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into the ice cubes and breaking the bonds that make them solid. The same thing happens when a liquid becomes a gas. It also happens in reverse when gasses condense to liquids or liquids solidify. In these cases, the change of state actually gives off huge amounts of heat. In the human body, we depend on these processes when we sweat. The evaporation of water from the surface of the body has a strong cooling effect.

3.8 Water

Ok, now we're ready to talk about the most important compound in the human body: water. We already know that it is formed from two hydrogens and one oxygen. We already know that the oxygen is a little greedy with the electrons, and that this leads to a slight positive charge on the hydrogens and a slight negative charge on the oxygen.

What I haven't mentioned yet is the shape of the molecule. In the oxygen, it turns out that the orbitals that are involved in covalent bonds are not simple spherical shells. Instead, they stick out in four directions, equally spaced, to form a sort of pyramid. It looks kind of like one of the 4-pointed playing pieces from a game of jacks. Two of these orbitals bind to the hydrogens, and the other two each hold a pair of electrons. This means that all that extra negative charge on the oxygen is concentrated in these two orbitals, and the whole molecule is kind of bent into a kind of V-shape. The tips of the V are the hydrogens, and the bottom point of the V is the oxygen. Now divide the water molecule into a top half and a bottom half: ~~V~~. The two upper tips of the ~~V~~ are the hydrogens, and the bottom point is the oxygen. Notice that in a water molecule, everything above this horizontal line is positive and everything below it is negative. So, water is a DIPOLE, positive at one end and negative at the other, kind of like a bar magnet (although we're dealing with electricity, not magnetism, here). We say that water is POLAR. Other molecules can be polar as well. Some examples are ammonia and ethyl alcohol (the kind you find in alcoholic drinks).

There are many reasons that this dipole effect is important. One is that water molecules stick to each other very strongly. A special bond forms between the hydrogen of one molecule and the oxygen of another. This bond is called a HYDROGEN BOND, and it is very strong. In fact, sometimes one water molecule actually rips a hydrogen away from another molecule. We can write a chemical equation for this process:

$$\mathrm{H_2O + H_2O \rightleftharpoons H_3O^+ + OH^-}$$

Another way to think about this is that water molecules just rip each other apart, so that there are always some water fragments lying around

$$\mathrm{H_2O \rightleftharpoons H^+ + OH^-}$$

We call this process DISSOCIATION. The two ions that are produced are called the HYDROGEN ION (the positive ion in this equation) and the HYDROXIDE ION (the negative ion). In pure water, each of these should be present in equal amounts. However, adding other compounds can cause the proportions to get out of whack. When there are more hydrogen ions than hydroxide ions, we say that the solution (mixture) is ACIDIC. When there are more hydroxide ions, we say that the solution is BASIC or ALKALINE. And when we add an acid to a base, the two will neutralize each other. We'll have much more to say about this in the next section.

Another reason that the polarity of the water molecule is important is that it allows water molecules to interact strongly with ions and other polar molecules, but interact very weakly with non-polar molecules. We'll see more of the interactions with polar molecules in the next section, but it is important to note here that the reason oil and water don't mix is because water is polar and oil is non-polar. The water molecules are all strongly attracted to each other, so they squeeze out all the oil molecules. The oil then floats to the top of the water (because it is lighter) and forms a separate layer.

3.9 Solutions

I've already used the word "solution" in the section above, but I didn't define it. A solution is a "HOMOGENEOUS mixture" of compounds in liquid form. Homogeneous just means that it is the same throughout, and looks like there is only one substance. For example, when you mix salt into water, the salt will soon DISSOLVE, and you will have a SOLUTION of salt in water. It will look just like ordinary water, and unless not all of the salt dissolves, there will be no lumps of salt floating around. A solution in which the liquid part is water is called and AQUEOUS solution.

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The liquid part is the and the part you mixed in (like the salt) is called the SOLUTE. The amount of solute in a volume of solvent is called the CONCENTRATION.

Solutions in water arise because of hydrogen bonds. The water sticks to the solute so that it is pulled apart into its component molecules, which float around in the solution. For example, in water, salt gets pulled apart into sodium ions and chloride ions:

$$\mathrm{NaCl} \rightarrow \mathrm{Na}^{+} + \mathrm{Cl}^{-}$$

Often, the solute molecules get pulled apart, but then they come back together. For example, acetic acid (vinegar) loses one of its hydrogens in water, but sometimes a hydrogen ion gets reattached. In the following equation, I've written an extra "H" to draw your attention to the hydrogen that leaves:

$$\mathrm{C_2H_5OH} \rightleftharpoons \mathrm{C_2H_5O^{-}} + \mathrm{H^{+}}$$

The negative ion that is produced is called the *acetate* ion.

3.10 Concentration, Moles and Molarity

Concentration, as I said before, is the amount of solute in a given amount of solvent or solution. The amount of solvent can be measured in liters or kilograms, but the solute is usually measured in units called MOLES. No, not the small blind animals that dig underground. The word "mole" means "lump," as in molecule – a very small lump.

We use moles because we want to have a sense of how many molecules of solute are in solution, not just their total weight. Let's say that we want to make two equally concentrated solutions: KCl and NaCl. We want both solutions to have the same number of molecules in them, but potassium and sodium have very different weights and sizes per atom. How do we do it?

Here's where the moles come in. A mole is just a number, like a dozen (12) or a score (20) or a gross (144). But it's a huge number and it was very carefully chosen. A mole is 6.02×10^{23}. It turns out that this is the number you need to convert atomic mass units into grams. So, a mole of hydrogen ions (H^{+}) weighs one gram, and a mole of hydrogen gas (H_2) weighs two grams. Another way to say that is that H_2 weighs 2g per mole. A molecule of NaCl weighs 58.5 atomic units (Na=23, Cl=35.5), so a mole of NaCl weighs 58.5 grams. Similarly, a molecule of KCl weighs 74.5 atomic units, so a mole of KCl weighs 74.5 grams. We can also say that the MOLAR WEIGHT of NaCl is 58.5 g and the MOLAR WEIGHT of KCl is 74.5 g. Notice that a mole of one substance can have a very different weight from a mole of another substance.

But, back to our salt solutions, we can now answer the question. In order to put the same number of *molecules* into solution, all we need to do is measure out the same number of *moles* of salt. Let's say we want to add one mole of salt to each solution: one solution will get a mole of NaCl, and the other will get a mole of KCl. So, we add 58.5 grams of NaCl to one solution, and 74.5 g of KCl to the other.

Now that you have equal numbers of molecules (or moles) in solution, how do we describe or measure the concentration? There are several ways to do that, but the one that is most important to chemists is called *molarity,* abbreviated *M.* Molarity is defined as the number of moles in the solution, divided by the number of liters that the solution occupies: $M = \frac{\#\,of\,moles}{\#\,of\,liters}$. A solution in which one mole of solute has been dissolved in one liter of water is a "one molar solution, " or 1M. A two molar solution has 2 moles dissolved into each liter of water. A solution with 5 moles of solute dissolved in 10L of water is a 0.5M solution.

Let's look at our real-world examples again. A 1M solution of NaCl has 58.5 g of NaCl for every liter of water, and a 1M solution of KCl has 74.5 g of KCl for every liter of water. If we took that 74.5g of KCl and added it to 2L of water instead of 1L, we would have a 0.5M solution.

Let's try a conversion problem, of the kind we saw in the math chapter. How many grams of NaCl do you need to make up a 3L batch of 2M NaCl solution?

Here's the information we have:

- We start with 3L of solution
- 2M = 2mole/L
- 1mole of NaCl = 58.5 g.
- We need to find the number of grams of NaCl

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$$3\ L \text{ of solution} = \underline{?}\text{g of NaCl}$$
$$3L \times \frac{2mol}{L} \times \frac{58.5g}{mol} = \underline{?}\text{g of NaCl}$$
$$3\cancel{L} \times \frac{2\cancel{mol}}{\cancel{L}} \times \frac{58.5g}{\cancel{mol}} = 351\text{g of NaCl}$$

One last note. Sometimes chemists and biologists want to use the molarity of a solution as a variable, or they need a shorthand for the phrase, "molarity of x". In that case, they will use square brackets, like so: [x]. For example, I could have stated the problem above as, "You are making a solution of NaCl. If volume = 3L, and [NaCl]=2M, how many grams of NaCl do you need?"

3.11 Equilibrium

When you first add acetic acid to water there are no acetate ions, but they are made quickly as the acetic acid dissociates. So initially, the forward direction of this reaction is fast, and the reverse direction is slow. As the acetic acid gets broken down, there is less of it, so the forward reaction slows. At the same time, the amount of acetate ion increases, so the reverse reaction can increase. Eventually, a sort of balance is reached, which is called EQUILIBRIUM. In equilibrium, the amounts of compounds from the right and left side of the equation do not need to be the same. However, the *rate* of the forward and reverse reactions *are* the same. There might be twice as much acetate as acetic acid, but the amounts won't change any more; for every acetate ion produced, another one recombines with a hydrogen ion to form acetic acid.

3.12 Acids and Bases

Hang on to your hat. This is a section that pulls together lots of information from lots of other sections, including math. If you have trouble with anything that is presented here, the best idea is to go back and review the previous material. That's ok! It's how we learn. Here goes!

3.12.1 Acids

We've all heard of ACID. It's that awful liquid that burns your skin, right? In movies and comic books, the hero is often found tied up and suspended by a rope above a huge, seething vat of the stuff. But what is it really?

Acid is half of a broken water molecule: the hydrogen ion. Technically, we say that an acid is anything that can donate a hydrogen ion. In high concentrations, it can react strongly with other substances, especially metals, usually by trading electrons. For example:

$$Cu + 2H^+ \rightarrow Cu^{2+} + H_2$$

In this case, Cu is copper metal, and Cu^{2+} is a copper ion. In other words, a pair of hydrogen ions can pull two electrons off of a copper atom. The hydrogen then bubbles away as hydrogen gas and leaves the copper ion in solution.

But hydrogen ions don't always have such strong effects. In fact, in biology, the most important effects don't involve electron transfer. Hydrogen ion can make its presence felt just by glomming on to some other compound. Let's take a look at a pair of reactions: the dissociation of HCl, and the dissociation of acetic acid.

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

$$C_2H_5OH \rightleftharpoons C_2H_5O^- + H^+$$

In the first reaction, hydrochloric acid (HCl in water) breaks down into hydrogen ion and chloride ion. In fact, whenever you add HCl to water, it will break down completely like this. in the second reaction, acetic acid (the active component of vinegar), also breaks down to give a hydrogen ion. The other thing that is produced is the "acetate" ion ($C_2H_5O^-$). So, acetate is just acetic acid with one hydrogen ion removed.

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But what happens when we put both HCl and acetic acid in solution *together?* Notice that the dissociation of acetic acid is reversible. In an actual beaker of acetic acid in water, some of it is in the acid form, and some is on the acetate ion form at any time, and those hydrogen ions are always kind of popping on and popping off. But if we add hydrochloric acid, there is even more hydrogen ion lying around than usual. That extra hydrogen ion *also* wants to combine with the acetate ions (to form acetic acid), and some of it gets the chance to do so. The result is that there is a little less acetate in solution – it has been turned into acetic acid.

This kind of reaction – the subtle shifting around of a few hydrogen ions between different acids – can have big effects in a biological system, because that acetate ion can bind to things that acetic acid can't. And of course, acetate isn't the only compound that reacts in that way. Any kind of acid could work the same way – including such famous examples as nucleic acids and amino acids. They both react differently when they are in the acidic form than in that other form. Say, what is that other form called, anyway?

3.12.2 Bases

Hopefully, you've guessed the answer: when you pull a hydrogen ion off of an acid, you get a BASE. Sometimes, it is called the "conjugate base." A solution that has a lot of base in it can be called "basic" or "alkaline." And, just like you can add hydrogen ions to a solution to make it acidic, you can add "the other half of water" to it to make it basic. The other half of water, of course, is OH^-, the "hydroxide ion."

$$H^+ + OH^- \to H_2O$$

Finally, if we add a base to an acid, we get water and a salt. For example, if we add the base sodium hydroxide to hydrochloric acid, the hydrogen ion will combine with the hydroxide ion to form water. Meanwhile, the sodium ion will combine with the chloride ion to give normal table salt.

$$NaOH + HCl \to H_2O + NaCl$$

In fact, there are many different types of salt, each formed from the reaction of a different base with a different acid. Look at the two examples below:

$$KOH + HCl \to H_2O + KCl$$

$$NaOH + \text{Acetic Acid} \to H_2O + \text{Na}\cdot\text{Acetate}$$

The first is the reaction of potassium hydroxide with hydrochloric acid to give water and the salt, potassium chloride. The second is the reaction of acetic acid with sodium hydroxide to give water plus the salt, sodium acetate. Of course, if you were to actually mix these things in solution, the salts would dissociate into dissolved ions. But the water would remain more or less whole. If you boiled away the water, you'd be left with the salts.

Before we move on to the next section, I want to briefly mention a very important base: ammonia (NH_3). This is the same stuff that we use as a household cleaner, although the bottle under your sink also contains some water, and maybe coloring and lemon oil. It happens that the nitrogen in ammonia acts very much like the oxygen in water, except that it can bind to three protons instead of two. Generally speaking, ammonia doesn't come apart very often in biological solutions. But if the solution is acidic, a molecule of ammonia can absorb a proton:

$$NH_3 + H^+ \rightleftharpoons NH_4^+$$

So, ammonia is a base. Its conjugate acid (on the right side of the equation) is called ammoni*um ion.*

3.12.3 Measuring Acidity: pH

So when we say that something is "very acidic," what do we really mean? In chemistry, we measure the acidity of a solution by finding the concentration of hydrogen ions in solution: $[H^+]$. It's good to have a reference point. In pure water (which is considered neutral: neither acidic nor basic), $[H^+]=10^{-7}$M. That's because at any time, one molecule of water out of every 10,000,000 is broken into a hydrogen ion and a hydroxide ion. Notice that in pure water, the concentration of hydrogen ion equals the concentration of hydroxide ion: $[H^+]=[OH^-]$. Again, *this only works in pure water!* But it turns out that in any solution of water, the hydrogen ion concentration *times* the hydroxide ion conentration is always equal to 10^{-14}, or $[H^+][OH^-] = 10^{-14}$ in *any* aqueous solution. This means that if we know the concentration of one of the halves of water, we can calculate the other. But because the calculation involves negative exponents, it turns out to be easier to use a scale called the pH scale.

"pH" means "the negative logartithm of Hydrogen ion." In math-speak, we would say:

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

Chemists also use that "p" to mean the negative logarithm of other things, but we don't have to worry about that yet. For now, just notice that the pH of pure water is 7, because -log(10^{-7})=7. This makes life much easier for chemists because they can just add and subtract pH's (rather than multiplying and dividing exponents) to calculate ion concentrations. For us, however, it causes a small problem because it makes everything look backwards. You'll just have to get used to it. Here's the rule:

The *higher* the pH, the more *basic* the solution.
The *lower* the pH, the more *acidic* the solution.
The closer the pH is to 7, the closer it is to neutral.

So, a pH of 2 is very acidic, but a pH of 14 is very basic. A pH of 5 is mildly acidic, while a pH of 9 is mildly basic. The pH of most living systems (like the inside of a cell) is a hair over 7. The pH needs to stay near that mark, because if it dosn't all the proteins and nucleic acids will change shape and stop working. We'll talk more about this later.

3.12.4 Some Important Facts and Examples of Acids and Bases

First of all, I want to point out a useful piece of information. It's mostly useful to me, as an author, because it saves a little bit of typing. A hydrogen ion is really just a proton, isn't it? Think about it. The hydrogen ion has a charge of +1 and has no electrons. So, it has to be just a plain proton, floating around in solution. Because this is true, and because it's easier to type one word than two, from now on I'll be using the terms "hydrogen ion" and "proton" interchangeably. So there.

I've already mentioned that some acids hold on to their hydrogen ions more loosely than others. What I didn't tell you is how we name these different kinds of acids. Acids that want to dump that extra proton are called STRONG ACIDS. Those that hold on to the proton are called WEAK ACIDS. Similarly, there are strong and weak bases. A strong base wants to glom on to a proton. A weak base doesn't attract protons very strongly. There are two things you should realize about these terms. First of all, don't confuse the *strength* or *weakness* of an acid or a base for the *concentration* of the solution. The words "weak" and "strong" in this context refer only to the binding of the hydrogen ion. A weak acid can still be very caustic (i.e it can burn) if there is enough of it in solution. Pure acetic acid, for example, is very caustic; however, it is still a weak acid, because not all of those protons get released at once. By the way, pure acetic acid is actually a liquid at room temperature, and you will often see it called *glacial acetic acid.*

The other useful thing to remember about weak and strong acids and bases is how they are all related to each other. You already know that when you remove a proton from an acid, you get a base, called the conjugate base, and when you add a proton to a base, you get the conjugate acid. Well, take a second to think about the conjugate base of a strong acid, like HCl. That chloride ion really doesn't hold on to the proton much at all. So, if you have a lot of chloride ions in a solution, none of them really wants to pick up a spare proton. That makes the conjugate base a WEAK BASE. If we started with a weak acid, however, the conjugate base would be STRONG.

3.12.5 Buffers

We're almost done with acids and bases (although in biology, we never leave them far behind). The last thing we need to discuss is something called a BUFFER. We're actually getting into pretty advanced chemistry, here, but it's very important for understanding how pH is maintained in the body, so hang on.

A buffer is something that resists change, kind of like a big stone wheel. If the wheel isn't moving, you'll need to push pretty hard on it to get it to start. Once it's moving, you'll need to push very hard to get it to speed up, or push very hard in the opposite direction to get it to stop. The mass of the wheel acts like a buffer on its velocity.

We also have buffers of pH. These are compounds that can resist a change in the acidity or alkalinity of a solution. A pH buffer is kind of like a sponge that soaks up hydrogen ions, and can release them later.

There are many pH buffers. Usually, they are made up of a combination of a weak acid and its conjugate base, together in a solution. So, sodium acetate and acetic acid, together, constitute a buffer. If you add HCl to such a solution, the sodium acetate can absorb the extra hydrogen ions (most of them anyway). If instead you had added NaOH, then some protons would be liberated from the acetic acid to absorb the hydroxide. Either way, the actual

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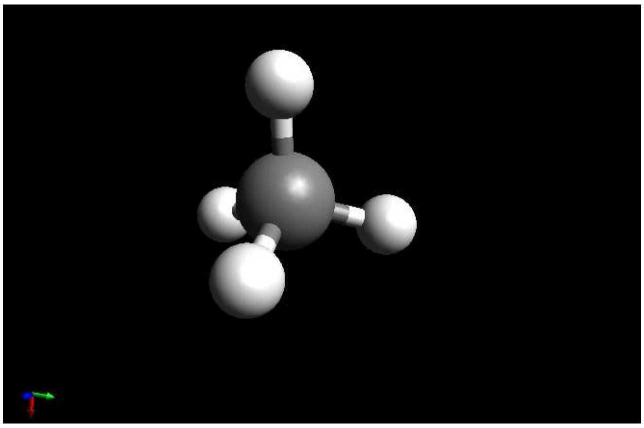


Figure 3.1: A molecule of methane

concentration of hydrogen ions in solution would not change very much – at least not compared to the amount of extra acid or base you added – because the excess gets absobed or released.

In biological solutions, the two most important buffers are the bicarbonate buffer system and the phosphate buffer system. Both systems are a little complicated because the acid/base can exist in more than just two states.

Phosphoric acid is H_3PO_4. It can lose one, two or even three protons, to form three kinds of conjugate bases: $H_2PO_3^-$, HPO_3^{2-}, or PO_3^{3-}. The middle two act as both weak acids *and* weak bases, which makes their buffering capacity very good. Sodium phosphate buffer is added to saline water for intravenous infusions, to make sure the pH is stable and correct for the body.

Bicarbonate ion is the body's natural buffer, and it is also the form in which the blood carries carbon dioxide. Have a look at the following reaction:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3$$

In this three-step process, carbon dioxide combines with water to form carbonic acid. The carbonic acid can then give off a proton to form bicarbonate ion. Since there is always a little of all three present in the blood, pH is buffered. If there is too much hydrogen ion, carbonic acid is formed. In the lungs, we can then convert the carbonic acid into carbon dioxide and breathe it out. If the blood is too alkaline, the carbonic acid can supply protons to neutralize it.

By the way, ammonia works as a buffer too. It becomes very important when you study the kidneys and the pH of urine.

3.13 Organic Chemistry: Carbon Compounds

Charcoal is made almost completely of carbon. It's black and turns powdery when you crush it. But the diversity of carbon compounds is immense and varied. Diamond is also pure carbon. So is graphite. The diveristy comes from the fact that carbon atoms can form many kinds of molecules, and can bond to itself in long chains, sheets or even three-dimensional structures.

Carbon has unpaired electrons in its outer shell, so it can form four covalent bonds. That means it can bond to as many as four other atoms. In biology, the other atoms are usually hydrogen, oxygen, nitrogen or sulfur. And, of course, carbon can also bond to itself.

Carbon's four bonds don't all lie in the same plane like the four directions of the compass. Instead, they each point toward the outer corners of a shape called a TETRAHEDRON, which is a pyramid made from four triangles. In the following diagram, you can see a dark carbon atom in the center of one of these pyramids, with four lighter hydrogen atoms surrounding it. This molecule is called METHANE.

If there were two carbons bound to each other, with three hydrogens bound to each one, the molecule would be called ETHANE. Here is a molecule of ethane:

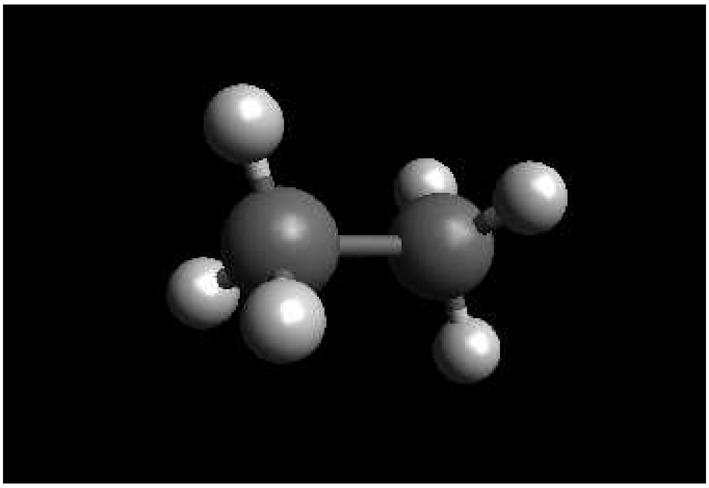


Figure 3.2: A molecule of ethane

3.13.1 Hydrocarbons

Compounds like methane and ethane, ones that contain only carbon and hydrogen, are called HYDROCARBONS, and they are always non-polar. Hydrocarbons tend to take the form of long chains of carbons, often with branches. In general, shorter hydrocarbons are more likely to be gasseous at room temperature, and longer hydrocarbons are more likely to be liquid or even solid at room temperature. For example, tar is made of very long-chain hydrocarbons. The carbons can be bound to each other with single, double or triple bonds, so long as each carbon atom only has a total of four bonds. Each hydrogen can only bind to one other atom at a time – the carbons, in this case. If the bonds between carbons are all single bonds, the number of hydrogens can be calculated easily: H=2C+2. If there are double or triple bonds, then finding the number of hydrogens gets more tricky. Some well-known hydrocarbons include benzene and toluene (which are often used as non-polar solvents), propane, acetylene (used in oxy-acetylene torches), and butane. Gasoline is a mixture of many compounds, but nearly all of them are hydrocarbons with somewhere around eight carbons (an eight-carbon chain, by the way, is called OCTANE). Unrefined petroleum is a mixture of thousands of kinds of hydrocarbons, ranging from very short to very long. Each has slightly different properties. The job of an oil refinery is to separate out all the different kinds of hydrocarbons, so they can be used for different purposes.

The shape of these hydrocarbons – and other organic compounds as well – can be drawn or represented in various ways, and you might see any of them in your courses. The easiest is a sort of modified chemical formula. Take PROPANE, for example. Normally, we would write its chemical formula as C_3H_8, but that doesn't give us an idea of what it looks like. Instead, we might write out: CH_3CH_2CH_3 (or CH_3-CH_2-CH_3). This form gives us the impression of a chain of carbon-hydrogen units, but notice that it means the same thing. It has the same number of carbons and hydrogens. Of course, we could also draw out a nice picture of this molecule, like so:

3.13.2 Alcohols

Huge numbers of compounds can be made with just carbon and hydrogen, but we can also add other atoms, such as oxygen or nitrogen, to form other categories of molecules.

We've already seen two of these other groups: the carboxylic acids (also called organic acids), and the alcohols. Alcohols are compounds that have an OH group in them some where. That OH group is not charged like a hydroxide ion, but it is polar (like water), and we call it the HYDROXYL GROUP. Ethanol, for example (the stuff that college students have been known to drink on occasion), is a two-carbon chain, just like ethane, but one of the hydrogens is replaced with a hydroxyl group. Its formula is $\mathrm{CH_3CH_2OH}$, and it looks like this (the red atom is oxygen):

Other alcohols include methanol ($\mathrm{CH_3OH}$), and iso-propyl alcohol ($\mathrm{CH_3CHOHCH_3}$). Butanol, a four-carbon alcohol, is currently being studied as an alternative fuel. But to show these, it would be easier if we could leave out some of the details. We can draw simple stick diagrams of any organic compound, in which only the bonds and the more exotic atoms are shown. We assume that everything else in the chain is a carbon, and that each carbon has the right number of hydrogens.

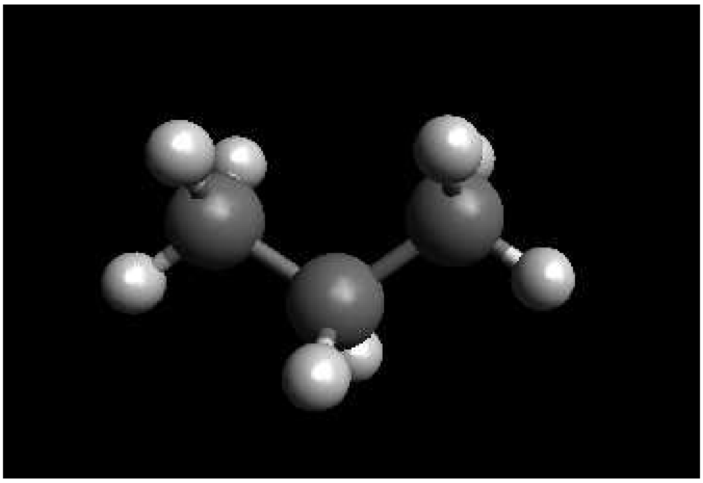


Figure 3.3: A molecule of propane

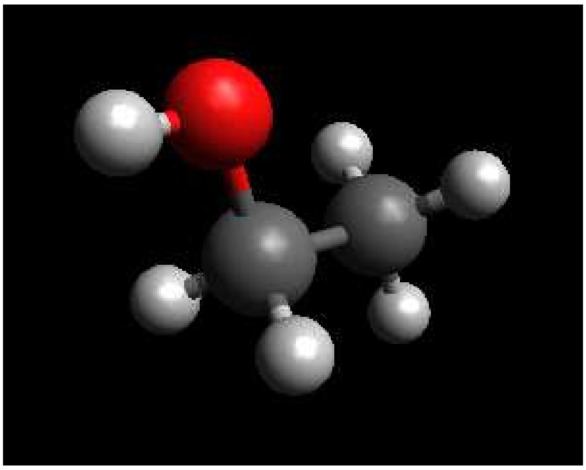
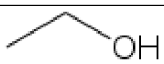
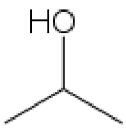


Figure 3.4: Ethanol, a college student's best (and worst) friend.

Table 3.2: Some stick diagrams of common hydrocarbons and alcohols.

Name	Diagram	Comments
propane		Three carbons, with one bond between each.
butane		Four carbons with one bond between each
prop*e*ne		Three carbons, with a double bond between two of the carbons
ethanol		Two carbons with an -OH group attached at the end
isopropyl alcohol		Three carbons, with an -OH group attached in the middle.

The oxygen in all the alcohols make them more polar than the hydrocarbons, but the longer the chain of carbons, the less polar they are. Ethanol will dissolve in water easily, but the alcohols with more than 10 carbons don't; they act more like oils.

3.13.3 Organic Acids

The second class of oxygen-bearing compounds that we've seen are the ORGANIC ACIDS. In an organic acid, there are two oxygens bound to the same carbon: one is doubly bonded, and the second is singly bonded and capped off with an oxygen (like an alcohol). The example we've seen before is acetic acid, the "active ingredient" in vinegar. It's shown here.

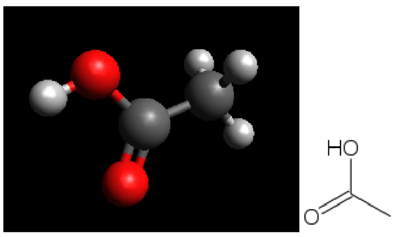


Figure 3.5: Acetic acid, the active component in vinegar

Notice that one of those carbons has three bonds to two oxygens. Now, the importance of these three bonds is that they sort of re-inforce each other so that they are very stable (this is real quantum-dynamic weirdness, by the way). They are so stable that one of the oxygens can break its "two bonds" rule. It can lose its hydrogen, in the form of a proton – just like all the acids we saw before – leaving behind a negative charge. The conjugate base of this acid is called ACETATE.

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3.13.4 Ethers, Esters and Hydrolysis

There are two more kinds of oxygen-bearing molecules that we need to see: ETHERS and ESTERS. You will probably never have to tell them apart, but you will definitely see them. Both of these groups are important because they allow our cells to link certain organic molecules together.

Ethers are simple. An ether is a pair of organic molecules, linked together by a single oxygen. The anaesthetic DIETHYL ETHER ($CH_3 - CH_2 - O - CH_2 - CH_3$) is the most famous one (it's the one that puts you to sleep), but you will also see ether linkages when you study carbohydrates. *Ether linkages allow two sugars to be joined together.*

ESTERS are like ethers with a second oxygen. Many flavorings and scents are esters; wintergreen is an excellent example. But the real reason these are important is that ester linkages hold together a huge class of oils and fats, called a TRIGLYCERIDES. An ester looks sort of like an ether, but next to the oxygen that forms the bridge, there is a carbon that has another oxygen on it, double-bonded. It also looks kind of like an organic acid, only there is another whole molecule where the removable proton should be. You can make an ester by combining an organic acid with an alcohol. Figure 3.6 is an ester; don't worry about its name.

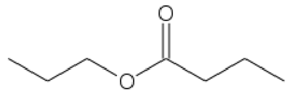

Figure 3.6: An ester.

Next, have a look at how that ester can be formed. You start with an alcohol and an acid, and when you combine them, you get an ester plus a molecule of water.

The place we see esters in biology is in the fats. We'll see later (in the section on LIPIDS) that some fats can be hooked up together. The ester acts as a kind of hook-and-loop closure between the parts of the fat molecules, and it can be fastened or unfastened depending on the pH of the solution (they tend to be unfastened in a basic solution).

Whenever we make an ether or an ester linkage, a molecule of water is produced, as in figure 3.7. And when we want to break an ether or ester linkage, a molecule of water is split apart in the process. So, a reaction in which we link two biological molecules is called a CONDENSATION reaction – because water seems to condense out of them – and a reaction in which we split a biological molecule in two is called a HYDROLYSIS reactions because water is split. We also see condensation and hydrolysis in the formation of proteins and chains of nucleic acids.

3.13.5 Nitrogen and Everything Else

We are nearly done with our tour of organic chemistry, but we have only scratched the surface of its complexity. Suffice it to say that many kinds of atoms could be attached to carbon, making a nearly infinite array of possible compounds.

Most importantly, there is nitrogen. The -NH_2 group is called an AMINE. Nitrogen can take three bonds (four if it wants to gain a positive charge), and has a pair of electrons sticking out, so it can act a little like oxygen in an

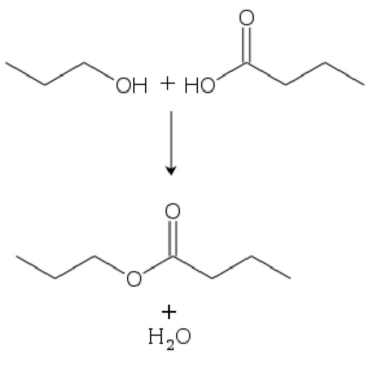

Figure 3.7: The formation of an ester from an alcohol and an acid. A molecule of water is also formed.

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organic compound. It is polar. Remember that ammonia (NH_3) acts a little like water? Similarly, an amine acts a little like an alcohol group. We'll see amine groups when we look at amino acids.

Nitrogen can also bind to *two* carbons, becoming part of the interior of the carbon chain or ring. We'll see that arrangement when we look at nucleic acids.

3.14 The Four Categories of Macromolecules

This section contains concepts that your professor will probably teach you in class – i.e. things that you are probably not expected to know already. However, not all professors are alike, so an extra review can't hurt. It will also help to show why the previous section is important.

Let's take a quick look at what kinds of molecules there are in our bodies. There are, of course, millions of different compounds in our bodies, and they fall into many categories. However, there are only four categories of molecules that form very large compounds: the MACROMOLECULES.

The four macromolecules are

- CARBOHYDRATES,
- LIPIDS,
- AMINO ACIDS, and
- NUCLEIC ACIDS.

3.14.1 Carbohydrates

Carbohydrates we have seen briefly. They include the sugars and starches, but also other materials like cellulose (used by plants to build cell walls), glycogen (used by animals to store energy) and chitin (used by lobsters, insects and other creepy-crawlies to form shells). Carbohydrates are compounds that have the general formula $[CH_2O]_n$, which means that the number of carbons is the same as the number of oxygens, and there are twice as many hydrogens. That's only an approximate definition, but it works pretty well.

For the purpose of your course, the basic unit of a carbohydrate is the MONOSACCHARIDE, or SIMPLE SUGAR. Each kind of monosaccharide has five or six carbons, five or six oxygens and ten or twelve hydrogens. The carbon chain is actually ring-shaped, with hydroxyl groups or double-bonded oxygens on each carbon. Each kind of monosaccharide is determined by the exact arrangement of these hydrogen, oxygen and hydroxyl groups.

The most important monosaccharides are GLUCOSE and FRUCTOSE, which each have six carbons, and RIBOSE and DEOXYRIBOSE, which each have five carbons. Monosaccharides can be linked into chains of these little rings. Two monosaccharides linked together are called a DISACCHARIDE. Table sugar, SUCROSE, is a disaccharide of glucose and fructose. Technically, three monosaccharides bound together are called a trisaccharide, but we hardly ever use that word. Instead, we refer to short chains of monosaccahrides – in the neighborhood of three to ten units long – as OLIGOSACCHARDES. In biology, we mostly see oligosaccharides on the surface of cells. Sometimes they are made of special sugars that carry a negative charge, which makes them repel other cells. Sometimes they are sticky, which helps cells bind together. Sometimes, they bind only to specific other sugars, which helps cells recognize each other.

When lots of individual sugars are bound together, we call the molecule a POLYSACCHARIDE. Starch is a polysaccharide, made of glucose molecules that are linked together into a long chain. Plants use starch to store energy, and we use it as food. Plants also make another polysaccharde, cellulose, to use as a building material. The difference between starch and cellulose is just a small change in how the individual glucose molecules are bound to each other, but it makes a big difference for us. Our digestive system can break down starch into individual glucoses, but it cannot break down cellulose; cellulose is indigestible in humans. Dietary fiber is made of cellulose.

If the glucoses are bound together into a huge *branched* chain, we call the molecule GLYCOGEN. Humans use glycogen to store energy in our liver and muscles, and you will definitely be seeing it again when you discuss metabolism in class.

There is one final kind of polysaccharide, chitin, but it is not found in humans. Insects, lobsters and other arthropods (the "jointed-leg" invertebrates) use it to form their shells and outer coverings. It is also indigestible, by the way.

Before we close the section on carbohydrates, I want to discuss a word that we have used frequently without really defining. That word is "sugar." Sugar is not a scientific word. Scientists use it, however, to mean any

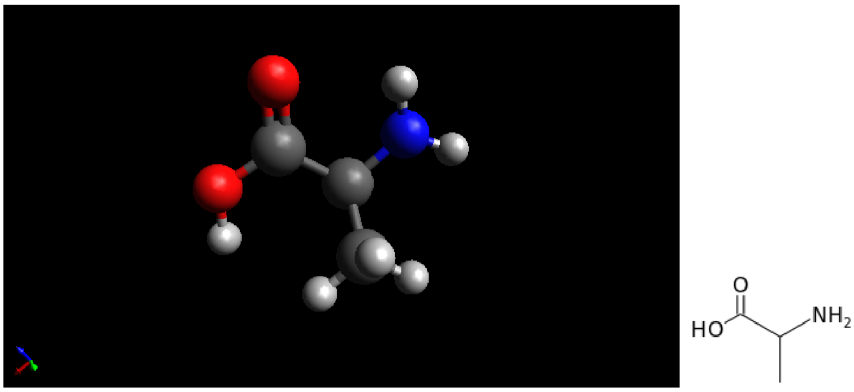

Figure 3.8: An amino acid, called alanine. Note the red balls, which represent oxygen, and the blue one that represents nitrogen.

carbohydrate that is short and sweet. Sometimes, when discussing the components of a polysaccharide, scientists will call its individual monosaccharides "sugar residues," or just "residues." This is because when you break up the polysaccharide in the lab, what you get is a bunch of left-over sugars in solution, or residues.

3.14.2 Amino Acids

We've already seen that sugars can bind to each other to form chains with many different properties. AMINO ACIDS are similar to the carbohydrates in this respect. There are many kinds of amino acids, and they can form long chains with different properties. There are two very important differences, however.

1. Amino acids can also form *enzymes,* super-specific catalysts that can control the chemical reactions in a cell.
2. Chains of amino acids can be encoded in DNA and passed from generation to generation.

So what are these amino acids? The basic structure is very simple: a two carbon chain, with an amine group on one end and a carboxylic acid on the other.

On the second carbon (the one one bound to the amine group), we have a SIDE GROUP, which can be just about anything, in theory. The simplest side group is just a hydrogen, and alanine has a methyl-group (-CH_3). Other possible side groups include benzene rings, or hydrocarbons with various oxygens. There are even side groups that contain sulfur. Each one has very distinct properties. Some are polar and some non-polar. Some are acidic and some are basic. Some are large (which limits their movement) and some are small. There are about 20 of them used by the human body, and each has a name. Some common ones are glycine, alanine, phenylalanine, serine, tryptophan and glutamate.

Amino acids can be bound to each other with PEPTIDE BONDS. Long chains of amino acids are called proteins or POLYPEPTIDES. You might have already guessed that a short chain of these critters is called an OLIGOPEPTIDE, and just two of them is called a DIPEPTIDE. These chains are almost never branched, but they can coil up in numerous diffrent ways to give different properties. Their coiling is determined by the properties of the individual amino acids in the chain: ones with hydrophobic side groups tend to lump together, and ones with hydrophilic side groups tend to repel them. An extremely important aspect of these proteins is that they take on intricate shapes, and two proteins can affect one another if they fit together like a lock-and key. In this way, proteins can form catalysts that only act on a specific compound (or a class of similar compounds). We call these special catalysts ENZYMES, and they control all the chemical interactions in the body.

3.14.3 Lipids: Fats and Oils

The third group of macromolecules is the lipids, which includes fat and oils, plus cholesterol and its derivatives. The difference between fats and oils is subtle. Oils are liquid at room temperature, whereas fats are solid. Usually, fats and oils have a long-chain hydrocarbon component, although this often has an organic acid group at one end. These long-chain acids are called fatty acids. A fatty acid can have all single bonds, or it can have some number of double bonds between the carbons. The ones with single bonds are called SATURATED FATTY ACIDS, because they

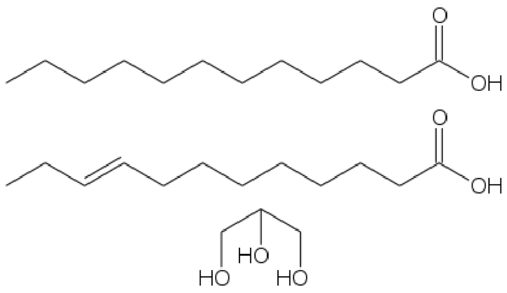

Figure 3.9: Top: a saturated FATTY ACID. Middle: an unsaturated FATTY ACID. Bottom: GLYCEROL

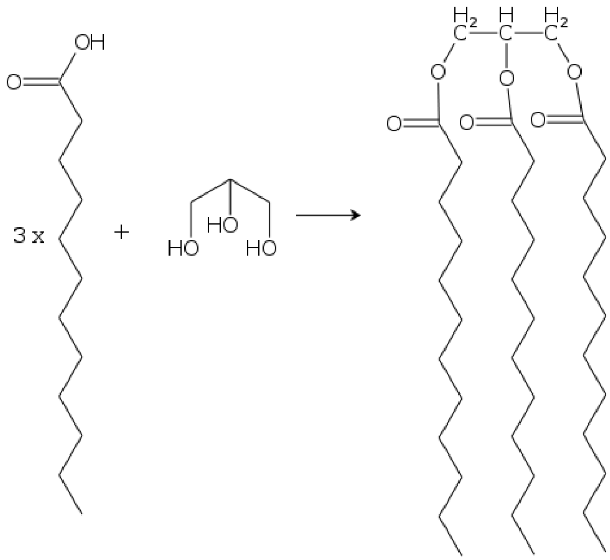

Figure 3.10: Making a TRIGLYCERIDE from three fatty acids and a glycerol.

are saturated with hydrogens. The ones with some double bonds are called UNSATURATED. The unsaturated fatty acids are supposed to be healthier to eat. In the body, fatty acids are often bound, three at a time, to a molecule called glycerol. Glycerol is a three-carbon chain with a hydroxyl (alcohol) group on each carbon.

Now, remember that I said before that an acid can bind with an alcohol to form an ester? That's what happpends when these fatty acids bind to GLYCEROL. The acid group on each of the fatty acids binds to one of the alcohol groups on the glycerol (giving off a water molecule in the process) to form an ester linkage. The resulting huge molecule, consisting of the glycerol plus the three long chains, is called a TRIGLYCERIDE. The body can build a triglyceride or break it down into its component parts (the fatty acids and the glycerol), using enzymes.

Triglycerides can be modified for many functions. The most important is the production of PHOSPHOLIPIDS, which make up the outer membrane of a cell. Each phospholipid is a *diglyceride* (a triglyceride minus one fatty acid), bound to a phosphate ion. Because it has an ion on one end, and a pair of long-chain fatty acids on the other end, it is both hydrophilic and hydrophobic. The phosphate wants to dissolve in water, but the fatty acids – especially the long-chain hydrocarbon portion of them – repels water. This fascinating property allows masses of phospholipids to arrange themselves into sheets. If you add a bunch of phospholipids to water and shake it all up, they will form little cell-like bubbles in the water, all by themselves.

Technically, the lipids include any biological molecule that is composed only of carbon, hydrogen and oxygen, and that is not completely hydrophilic. That's a wide swath of the biological compounds! But for our purposes, there is only one more lipid to discuss: cholesterol. Cholesterol is a lipid, but it has a distinctive four-ring structure. It also is found in the cell membrane, but it has other imortant functions: it is used as the template from which we build many hormones. Testosterone, estrogen and cortisol are all made by modifying cholesterol, and they all have that same four-ring structure. You will learn more about these hormones, and others, when you cover the

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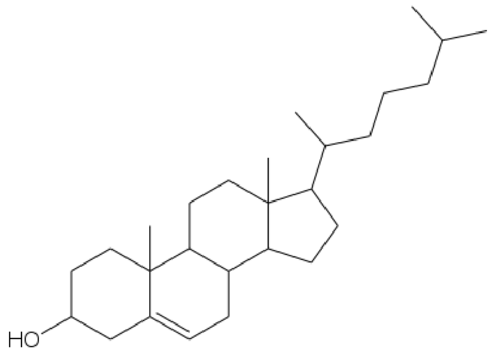

Figure 3.11: Cholesterol

endocrine system in your physiology class.

3.14.4 Nucleic Acids

The last, and arguably most important, class of macromolecules is the nucleic acids. This is a large group of coumpounds, but only five are used much in the body: cytosine, guanine, adenine, thymine and uracil. They have two interesting properties. The first is that they like to form pairs, based on hydrogen bonds. Cytosine bonds to guanine, and adenine bonds to thymine or uracil. The second is that they can be bound to the five-carbon sugars, ribose and deoxyribose. Those sugars, in turn, bind to phosphate ions, to form alternating chains: ribose-phosphate-ribose-phosphate... and so on, or deoxyribose-phosphate-deoxyribose-phosphate... and so on. The nucleic acids bind to each of the sugars on these chains, like little flags on a rope. The result is DNA (if the sugars are all deoxyribose) or RNA (if the sugars are all ribose).

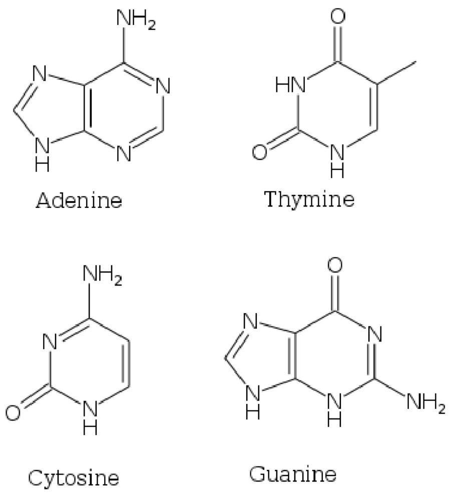

Figure 3.12: The Four Nucleic Acids of DNA. RNA uses uracil instead of thymine. Thymine and uracil look almost the same.

Remember that DNA stands for deoxyribonucleic acid, and RNA stands for ribonucleic acid. In a chain of DNA, the nucleic acids are ADENINE, THYMINE, CYTOSINE and GUANINE. In RNA, the acids are Adenine, URACIL, Cytosine and Guanine. Uracil looks like Thymine with a small branch sticking out. The way many students remember that it is *RNA* that uses uracil in place of thymine is that Uracil is the only nucleic acid that has an R in it. But what do these big chains do?

DNA stores information in the cell. Each chain is usually bound to another chain that has the corresponding nucleic acids on it. So, for each adenine on one chain, there will be a thymine on the other. For each guanine, there will be a cytosine, and so forth. The two chains are bound together like the two halves of a zipper, with the nucleic acids acting like the teeth. The order of the nucleic acids is a code that can be read by the cell to make proteins; each set of three nucleic acids stands for one of the amino acids. DNA can copy itself too – with the help of enzymes. If you separate the chains, free nucleic acids will bind to each side to make an exact copy of the other. From one chain, you get two perfect (or near perfect) copies!

RNA has multiple functions in the cell. It can bind to DNA and be used to carry information from one part of the cell to another. It can also act as an enzyme in its own right, especially in fuctions that involve decoding DNA. It is believed by some evolutionary biologists that the first life on Earth was actually RNA-based rather than DNA-based, because it can fullfill many of the functions of both proteins and DNA.

There is a third form that nucleic acids take in the cell, and that is the energy-carrier, ATP.

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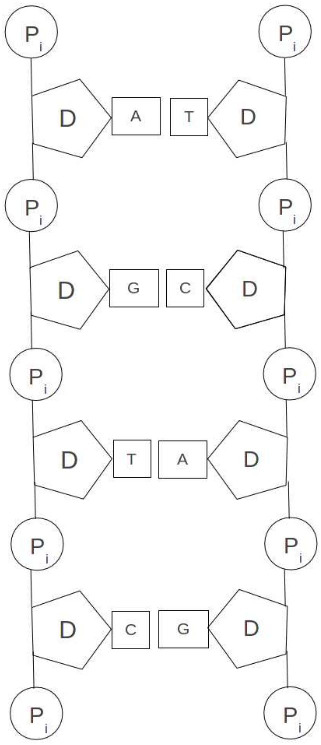

Figure 3.13: Two strands of DNA, side-by-side. In this diagram, P_i stands for Phosphate, D stands for Deoxyribose, and A, C, T, and G stand for Adenine, Cytosine, Thymine and Guanine. Notice that each Adenine is paired with a Thymine and each Cytosine is paired with a Guanine.

ATP stands for Adenine triphosphate. It consists of an adenine molecule, bound to a ribose, which is then bound to a chain of three phosphates. In effect, each phosphate acts like a one-shot battery that can be used to power a chemical reaction. When the cell uses an ATP, the molecule is converted to ADP (adenine diphosphate), and a free phosphate ion comes off. Energy is needed to put the phosphate back on for another use. You will learn much more about this subject when you discuss cellular metabolism in class.

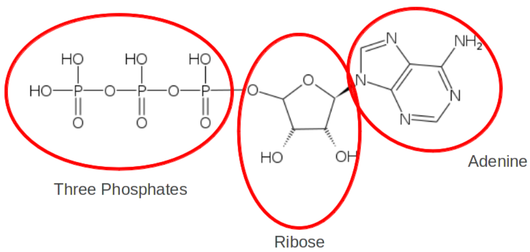

Figure 3.14: ATP

3.15 Last Words on Chemistry

Of course, there are countless other kinds of molecules in the body: oxygen and carbon-dioxide, iron and the other minerals, various small molecules that we use as vitamins, and chemical messengers of many kinds. Some are ions and some are neutral. Some are hydrophobic and some hydrophilic. Some have short life-spans in the body, and others hang around for a long time. Many blur the lines between the macromolecules. They can take on amazing properties, like little machines, or they can function just by filling space or carrying an electrical charge. But remember this: they *all* obey the laws of chemistry and thermodynamics, every piece of matter in the body. Always. No exceptions.

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