Lecture 1B • 09/27/11

First, an introductory type of question: what is organic chemistry? Since that is they course you are about to take. Anybody have an idea what organic chemistry is? The chemistry of carbon. Organic chemistry, the term, came from the fact at some point when chemistry was developed it was recognized that biological creatures such as us have a chemistry. But in the 1800s we were also able synthesize some of these same compounds. And so the term grew from being something that referred compounds that were biologically-based to more generally something that is carbon-based. So this entire course is going to be about the chemistry of carbon.

{Introduction to organic chemistry}

The first thing we are going to do is to bridge general chemistry to organic chemistry. There is often this rough sort of disconnect that occurs with students going from general chemistry to organic chemistry. Because in general chemistry you've been heavily mathematically immersed. You've covered topics such as thermodynamics, kinetics, equilibrium. Now we're entering a course in which you'll have almost no math. It's almost all concept. So for some of you that'll be a good thing if you don't like math; some of you who aren't as fond of concept you might struggle a little bit at first. What we're going to do at the beginning of the quarter then is to put organic chemistry into the context of general chemistry. So, we will start with a week of review of atomic and molecular structure, so that we can understand how the structure of a molecule effects its reactivity. We will then review topics such as thermodynamics, kinetics, and equilibrium, because we use those tools to predict the product of a reaction. If there are multiple products that occur we can try to predict which one of those is more likely. And then once we've covered that essential material we'll wind up with a quick review of acids and bases and then really jump into organic chemistry proper. In terms of organic chemistry what we're going to start with is mechanism. The fact that, these days, we are able to try to come up with not just a scheme of memorization, not just saying: here's some random molecule, let's do a reaction to transform it into something else; here's another random molecule, let's do some other reaction. Instead, we recognize that there are these things called functional groups – these characteristic patterns of atoms that, no matter what kind of molecule those show up on, they tend to have reproducible behavior. We also have a way of tracking which direction electrons go in a chemical reaction, which has greatly increased our understanding of organic chemistry. So we'll start with mechanism, and then discuss some consequences of mechanism. So, you've probably had stereochemistry in the past; you might have talked about cis/trans isomers; some of you might have even gotten to talking about enantiomers. Stereochemistry has a huge importance in the reactivity of organic molecules. We'll also talk about regiochemistry – when you have a long molecule, could it be that something substitutes at one position versus another on that molecule? Often, yes it does. Once we cover those aspects, then we'll start progressing from functional group to functional group. This quarter we'll focus on alkanes, alkenes, which are compounds with carbon-carbon double bonds, and alkynes, which are compounds with triple bounds. We'll then play with alkyl halides, which are carbon compounds that have a halogen on them.

First thing we'll do is: how do we even write down the structure of organic molecules. We'll also see an example of these functional groups – these characteristic patterns of atoms. We'll then cover the essentials of mechanisms: what are these arrows that you're going to start seeing. And then we'll round off with an introduction to synthesis: what is the goal of organic chemistry? To put it in a nutshell, if you have some inexpensive starting material, the goal of synthesis is to design a sequence of transformations that you can convert that cheap material in something very useful. That is going to be end goal of the quarter.

Let us start with what are known as line structures.

To show you an example of why we use these line or Kekulé structures, instead of the type of structures you might have written in Chem 1A, I want to start to write down the molecule oleic acid, which is one of the major constituents of olive oil, oleo, related to oleic acid. It is an eighteen-carbon compound. I'll start by writing out its carbon framework. There are eight carbons singly bound one to the next, with a double bond in the middle of the molecule, followed by yet another eight carbons, and at the end we have a couple of oxygens, with a hydrogen attached to that oxygen. This is not the complete structure, though, because in most cases, unless there is something special about the molecule, carbon tends to be what is known as tetravalent. You might remember the term valence shell from chem 1, valence meaning to have power over or control over. So valency refers to how many connections an atom has to another. So if I say that carbon tends to be tetravalent, that means it wants normally to have four bonds. But as you can tell from what I've drawn on the left-hand side so far, I've only got one bond currently to that carbon. So by default, unless there is some other symbol shown, the way that carbon naturally reacts, it's going to have hydrogens attached. So at the end we'll have three hydrogens, then two more hydrogens, and then two more. I could spend the time to fill the rest of it in, but you can already tell it's not the most rapid way of writing a structure. So let me show you the way we normally represent that in organic chemistry. Much, much, much quicker to write. And, with a little practice, far easier to read. You will very quickly get used to seeing just the skeletal framework and from that being able to interpret how many hydrogens are there.

Let me present to you the rules for going from this old style structure to this line or Kekulé structure. The first one that might be somewhat obvious is that we normally leave out carbon labels. So the atomic labels for carbons, because this is a system for writing organic molecules, that's why we make that assumption. So every place along this structure that's an end of a line or a point where the line changes direction, each one of those places is a carbon atom. So, for line structures, carbon atom labels and the hydrogens attached to those carbons, also, are omitted. It's not that you must always leave the hydrogens out. We'll see examples of why you would want to show the hydrogens explicitly to help show a mechanism, the way that electrons flow. Or, there will be times where we write the carbon explicitly. But as a general rule, carbon atom labels and atom labels for hydrogens attached to carbons are omitted.

Now, in reverse, when we read these structures, when you see fewer than four connections, which means four single bonds, a double bond and two single bonds, two double bonds, a triple and a single, any combination like that, if you don't see four connections to a particular carbon, that means automatically, unless there's some other symbol symbol or indication on the molecule, then you assume that there's enough hydrogens to bring that total count up to four. So, when reading a line structure, a carbon is assumed to be tetravalent, which means having four bonds, unless otherwise indicated. By convention, the "missing" connections are assumed to be hydrogen.

Let me give you a couple of terms. If you notice, there is a hydrogen that I explicitly wrote on this molecule. It's because, in this case, it's attached to an oxygen. There is a term, hydrocarbon, that means as it sounds – a molecule that only contains carbon and hydrogen. But many organic molecules don't contain just carbon and hydrogen – oxygen, sulfur, nitrogen, phosphorus, chlorine, bromine, those are common atoms that you would see. Since those are different from carbon and hydrogen, we refer to them as heteroatoms or "different" atoms. So those are elements other than carbon and hydrogen. In terms of rules for writing structures, heteroatoms and hydrogens attached to heteroatoms are always explicitly shown. Again, this is a system for writing carbon-based molecules, that's why we don't make assumptions about any other types of atoms.

You'll notice that in this structure, you'll see dots around the oxygens; what are those? Lone pair electrons. Lone pair electrons, single electrons, which occur in molecules known as radicals, and charges are always, always, always shown when writing structures – at least if you're doing it properly. Some textbooks for convenience will sometimes leave the lone pairs off of heteroatoms. i would strongly prefer (or require) that you always show your lone electrons, just so I can be sure you know what the correct configuration of each atom is. So, all charges and lone electrons must always be shown.There will be some exceptions to the first rule. There will be some cases where we explicitly write carbon and hydrogen.

I'd like to do a couple of quick examples. I'll write up a molecule written in the "old" style and I'd like you to convert it to a line structure; and then, I'll put a line structure up and I'd like you to convert it into a old-style structure.

Here's our first molecule. You may recognize a portion of this molecule.

Since this is the first time that some of you may be doing line structures, it's going to take you a while to get through. I just want to heavily emphasize that this is the one and only notation system that we'll be using for the class. Going to a line structure is fairly easy, since for the carbons, we just leave them out. So that means we're going to end up with a hexagon, where every other bond is a single versus double bond. That much of the molecule does anyone recognize what that is? Benzene, that's right. A question that was asked yesterday: does it matter if I write the double bond on the inside or the outside of the ring? No, it really is cosmetic. To write up the rest of the molecule, there's not that much to put on it, since all of the hydrogens that are attached to carbon, we leave them out. So there is just an -OH group that is attached to that. This is in fact the molecule phenol, a very common molecule, active ingredient in chloroseptic.

Now what about the other structure? How many carbons did you count for the other structure? I'm hearing the answer 6. Some of you might have counted five, and that might be because of the triple bond – if someone is going to get tripped up on a structure, it's often what someone gets tripped up on. The triple bond, by default, is between only two atoms. So you have one carbon that's on the left side of this triple bond and one carbon that's on the right side, but you see that we still have a line coming off of it. So that means, yes, there is another carbon at that junction. Then we have three other carbons, so there are a total of six carbons for this molecule. Now, the heteroatoms were already written in. To address another question that came up yesterday, someone asked: "could I write the answer where I don't show the bonds between nitrogen and hydrogen?" Yes, that's fine and very common; that's what would technically be called a condensed structure. That's the type of structure I will normally write. For mechanisms, you will sometimes want to show the bonds, just so you can show where the electrons in that bond are going. As far as the rest of the hydrogens on this molecule, for the carbon that's on the very left, how many hydrogens would need to be there? Just one. How about on the next carbon? None, because it's already got four connections: a triple bond and a single bond. What about the carbon next to it? Two. The next one over? Just one. The next one? None, already four connections. And then the last carbon? Two.

{question could not be heard}

There is what is known as a see-saw or a zigzag shape that many carbon molecules adopt, and you can see that I have that kind of shape here. Triple bonds have a linear geometry, so you have to write linearly like that. As far as which way the hydrogens point, generally, if you you're following the zigzag, and you have two bonds coming down to a junction, then whatever substituents attached to it point away from that connection center.

Since I've mentioned these functional groups, let me go ahead and point one out.

From your Chem 1A experience, if you saw that -OH group you'd be very tempted to call it hydroxide. But recognize that carbon-oxygen bonds are more covalent bonds. So, that -OH group is not going to dissociate at all into solution – not to any appreciable extent. In fact, this compound is a weak acid. It has a very low Ka which means a relatively high pKa. Does anyone happen to know in organic terms what that -OH is called? An alcohol. There is consumable alcohol – which happens to be a rather popular alcohol – but the alcohol term itself refers to just the fact that the molecule has this -OH group.

A functional group is a characteristic pattern of atoms that, regardless of the molecule you find it on, tends to have the same reproducible type of reactivity. Let's identify some of the other functional groups you've seen in the examples so far today. In our line structure problem, the triple bond is known as an alkyne; the double bond is known as an alkene; the nitrogen group is an amine; oleic acid has a functional group that you might recognize from chem 1 – carboxylic acid.

We won't study the reactions of alcohols but we'll learn how to produce alcohols.

One more bit of terminology. To substitute; change that to talking about the thing that is doing the substituting and that is the substituent. It's a group of atoms that takes the place generally of a hydrogen on some larger molecule. Yesterday, someone asked the question: "for phenol, does it really matter which carbon we right the -OH group on?" And the answer to that is no, because there aren't really double bonds on the compound. Delocalization. If you were to analyze benzene, each of the carbon-carbon bonds is identical in length. Why do we then write this down with single versus double bonds? Because these line structures are baed on Lewis structures which are based on a covalent model in which there's only two atoms involved. For benzene, there is a molecular orbital that in fact covers the entire carbon chain. That's why it has bonds with reactivity between those of single and double bonds. But, we will write these single and double bonds so that we can keep track of electrons. Someone else asked: "for things like benzene, can we write a little circle there?" Yes, you will commonly see a little circle in benzene, but I would say do not do it, for two reasons. One, when we learn these mechanisms, you do need to be able to keep track of where the electrons are; and two, that circle is somewhat imprecise. As we learn other molecules that also have this delocalization, circles and curves can become impractical to write.

Back to the question of what a substituent is, the -OH group is said to be a substituent of benzene, so it's something that took the place of hydrogen.

Nomenclature – the naming of molecules.

So that you can have an idea of how names are structured, let me write down three different compounds. Each of these has four carbons and one chlorine. These are, in fact, isomers, molecules with the same molecular formula. But, as you can see, they have different structures. In one case the chlorine is attached at the end of a four-carbon chain; the middle one, chlorine is attached in the middle; and then the last one, we have what is known as a branched molecule, where you don't just have a plain chain of carbons.

Organic compounds are named by a combination of what are known as common nomenclature and systematic nomenclature. Common nomenclature comes from the fact that we as humans have named substances far before we knew what their structures were. So, in the creation of nomenclature, some of those traditional names have stuck. In other cases, we have much more systematic names based on the number of carbons in a compound. So, for example, there is a compound hexane. Hexane. Hex- for six. Hexane refers to a compound that has six carbons. For smaller molecules, the traditional names tend to predominate. For example, methane, swamp gas, that's a one-carbon compound; ethane, two-carbons; propane, three carbons; and then butane, as in lighters, that's four carbons.

So these first two compounds are named as forms of butane. Of course they have something substituted on it. So this is sometimes substitutive nomenclature – we name how a framework molecule has been ornamented by these different functional groups. For chlorine, we use the prefix chloro-. But, we can't just say "chlorobutane" because these first two compounds would be both chlorobutane. So then we say where is the substituent located. There's a regular system for determining that. For these simple cases, you start numbering the chain from whichever direction the function group of the substituent is closer to. For this first compound, the right-hand carbon would be labeled as number one, and the same would be true for the second compound, since the chlorine is close to the right than the left. So the name for the first compound would be 1-chlorobutane, whereas the second one is 2-chlorobutane. When you see these locants, these numbers, they refer to where things are. And if you look at the names, if it ends in an "o" or "yl", it's one of these substituents.

Mechanism

A mechanism is the step-by-step flow of electrons in a chemical reaction. As an example mechanism, I want to do one of the most common types of reactions that occurs in organic chemistry, which is an acid-base neutralization. I was referring to the fact earlier than phenol is a weak acid. But, it can react with hydroxide, which in Chem 1A terms is a strong base; in organic terms, it's not that strong. If you were to take some organic molecules and remove a hydrogen to turn them into a base, they become so reactive that if you were to release the compound in air, it will actually burst into flames because of how violently it reacts with water in the atmosphere in an acid-base neutralization.

But, the conjugate acid of water has a pKa of 15.7, which is bigger than the pKa for phenol which is 10.0. Because of that, the conjugate of water – hydroxide – is a stronger base than the conjugate that would be produced from phenol.

Hydroxide is a base. Does anyone happend to remember the Lewis definition of an acid or a base? Lewis acids and bases don't have to involve a hydrogen. Bases are electron pair donors; acids are acceptors. So hydroxide is going to donate a pair of electrons to the hydrogen. The way that we show that is this kind of curved arrow. Another name for a mechanism is a curved-arrow formulism. It represents the fact that we represent the flow of electrons by these curly lines. Hydrogen can only have one bond at a time, normally. In borane-containing compounds there sometimes very unusual bonding that can occur. But for nearly every molecule that we see this quarter, hydrogen can only have one bond. Because of that, when hydroxide attacks the hydrogen of phenol, the oxygen-hydrogen bond is going to break, and the electrons are going to fall back to the oxygen. What will be produced then is a new ion. Phenol, when it becomes deprotonated, is called phenoxide. Our other byproduct will be water.

Let me comment that the tip of a mechanistic arrow shows where electron go to; the base of the arrow, then, shows where electrons come from. In the example that you see up here, when the base of the arrow comes from an atom, it implies that the electrons on that atom are the electrons that are going to be moving. As you can see, for the other mechanism arrow, the base is floating here between the bond between oxygen and hydrogen. That means that the electrons are going to come from that bond. In both case, the arrows point to an atom, and that means that a bond is going to be formed with that atom.

Mechanism arrows always show the flow of electron, not the atoms.

In this case where hydroxide is reacting, that arrow does appear to show where the hydroxide is going. But it's not showing that the hydroxide is moving that way; it's showing that the electrons from hydroxide are moving that way. To highlight this example: a hydrogen is actually coming off phenol, but the arrow is pointed the other way. That's because the hydrogen is not hydride; it is not H– leaving the molecule, it leaves as a proton, H+. It leaves its electrons behind – which then fall onto phenol. A mechanism arrow always, always, always, always shows where electrons move. If it happens to be that atoms move the same way that's fine, but it's not showing the direction that the atoms are moving.

The way that you write the arrow itself – the fact that I wrote a standard arrowhead – shows how many electrons are flowing. The vast majority of reactions we're going to learn involve something like this, where there are pairs of electrons moving around. But there is another arrow where you only show half the arrowhead. That means that just a single electron is moving around, which would occur in the case of a radical reaction. Radicals are molecules that have unpaired electrons. The vast majority of mechanism will be these electron pair mechanisms. Heterogenesis – the formation of a bond by lone-pair transfer; heterolysis – the uneven breaking of a bond. This is what's happening here; both the electrons went the same way. But another way that we'll see with radical reactions is for one electron to go to each atom in a bond, which is known as homolysis. And then there's homogenesis – the forming of a bond from electron with one other electron.

Synthesis

This is one of the most common type of problems I'll be asking on quizzes and exams. For example, I might have a molecule like ethanol, a two-carbon alcohol, that can react with the molecule phosphorus tribromide. It will form what is called bromoethane or ethyl bromide. There are two different names: a common name and a systematic name. Notice how I notate the flow of electrons. {erroneous statement – phosphorus in PBr3 has an incomplete octet} Oxygen has electrons that can donate into phosphorus. Once it does so, a bromine will be kicked out at the same time. The fact that these two events – the forming of a bond with oxygen and the breaking of the bond with phosphorus – is known as a concerted step. Once that has occurred, protonated oxygens (if they have hydrogens) are extremely acidic. Very rapidly, the oxygen-hydrogen bond will break. Here is an important point of convention. Since this is such an acidic molecule, it is possible for the hydrogen to fall off all by its own self. Some people are insistant that you always show where your hydrogens end up. I tend to find that sometimes students worry too much about the side reactions that occur and forget what the main point of a mechanism is. In general, when we have something like this that's an acid dissociation, by convention I won't show what happens to hydrogen. This arrow means the bond with hydrogen breaks and the electrons fall back to oxygen. This would indirectly have to mean that the hydrogen has disappeared. So we end up with this intermediate. In the last step, bromine comes in and attacks the carbon-oxygen bond, causing it to break, which is how we end up with a bromine in the place of where oxygen used to be.

Going back to the way I wrote the reaction, we have three things involved here: we have the starting material, which I will commonly refer to as the substrate; there is a well-known type of reagent that I have used that on many molecules with an alcohol, that PBr3 works on; we then have the product that's generated. One of the skills that you will acquire in this course is to be able to look at chemical reaction and if, for example, I should you the substrate and the product, you have to know what is the appropriate reagent. If I gave you the substrate and the reagent, you need to able to predict the product. And if I give you the reagent and the product, you need to be able to work retrosynthetically, to work in the reverse direction, to predict what would have been that substrate. This is what is lovingly known as a fill-in-the-blank problem. By your second or third exam you'll end up with a page where you'll have a series of these types of reactions where one or the other of the spots is missing.

In this case this molecules is reactive enough that even if there is nothing else around it, it will fall off on its own.

This does not show you why a reaction is occurring, it just shows you how it occurs.

Chapters one and two are a whole hodgepodge of topics. It is difficult to make the transition from general to organic chemistry. In chapter one there's atomic orbitals, molecular orbitals, bonding, molecular polarity, and then acid-base reactions, all stuck together in one chapter. Because our textbook does not match our flow of curriculum exactly, we are in fact going to be skipping carefully around from section to section to section.

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{Written notes missing for this day; see lecture on 09/26/11 for written notes}