

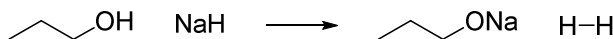
Loudon Chapter 10 Review: Alcohols & Thiols

Jacque Richardson, CU Boulder – Last updated 4/26/2016

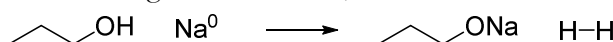
Alcohols (ROH) and thiols (RSH) have many reactions in common with alkyl halides, but they don't do everything exactly the same. The main difference between this and alkyl halide chemistry is that unlike a halogen, hydroxide (OH^-) is a bad leaving group because it's a strong base. The first few reactions involve converting the OH^- into a good leaving group, which allows them to do most of the reactions out of Ch. 9.

Acid-Base Reactions

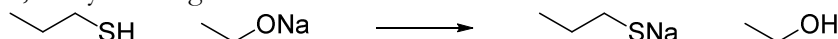
We've already seen that they can act as weak acids by donating a proton to any base stronger than themselves. This is because alcohols have pK_as in the range of 15-19, and thiols in the range of 10-12. Deprotonated alcohols are called alkoxides – we've already seen many examples in Ch. 9 like sodium ethoxide (NaOEt) or potassium tert-butoxide (tBuOK). The easiest way to form them is to start with the alcohol and deprotonate it with sodium hydride, NaH. This is a good choice because the byproduct that's created is H₂, which leaves the solution as a gas.



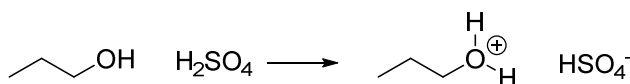
Another way to do this is by using sodium metal, Na. The mechanism for this is somewhat similar to the mechanism for Grignard formation, but we won't cover it.



Deprotonated thiols are called mercaptides. We've also seen some of these like sodium ethyl mercaptide (NaSEt). Since these have a lower pK_a, they can be made by either of the above two methods, or by reacting with an alkoxide.



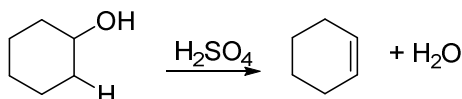
You can also protonate alcohols and thiols, because they're amphoteric. In this case, the relevant pK_a is for the conjugate acid, ROH₂⁺. The pK_a of this species is usually around -2, similar to H₃O⁺ at -1.7. All you need for this is an acid with a pK_a greater than -2, like H₂SO₄.



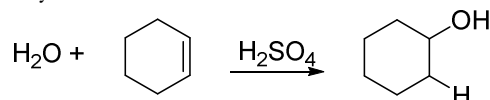
Both of these reactions – protonation and deprotonation of alcohols – will show up in various mechanisms during this chapter.

Acid-Catalyzed Eliminations

One way to convert the hydroxide to a good leaving group is to protonate it to OH_2^+ . This way, once it dissociates, it leaves as a neutral, stable H₂O molecule instead of a strongly basic OH⁻. If you use H₂SO₄, there's not really a good nucleophile around so the most likely outcome is elimination.



This reaction is exactly like hydration of alkenes but in reverse:



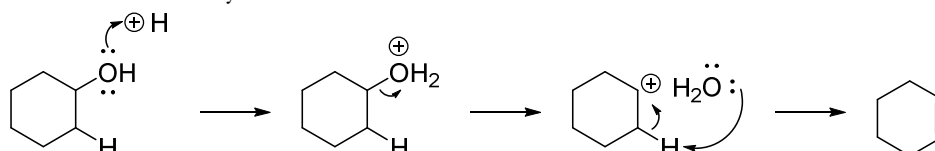
Since both reactions are catalyzed by acid, how do we control which direction is favored? We have to take advantage of Le Châtelier's principal: having more water present will drive

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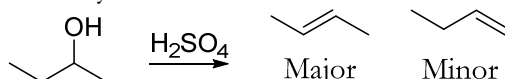
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the reaction towards the alcohol side, but having less water present will drive it towards the alkene side. We can remove water by using a strong, concentrated acid like H_2SO_4 or H_3PO_4 and adding it directly to the alcohol, with no water or solvent involved. We can also distill off the alkene as it forms, so that it's no longer in the presence of water.

The mechanism for dehydration of alcohols is exactly the same as the mechanism for hydration of alkenes, but in reverse. If you look at each intermediate, you should recognize it as an intermediate from hydration.



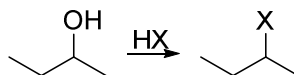
This mechanism also closely resembles the E1 mechanism we saw in Ch. 9, with the difference that the OH group needs to be protonated before it can dissociate. Just like in other E1 reactions, more substituted alcohols react faster, carbocation rearrangements are a possibility, and the regiochemistry follows Zaitsev's rule:



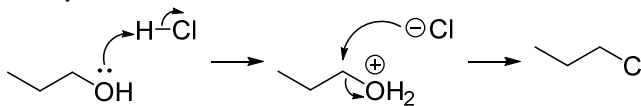
Converting Alcohols to Alkyl Halides or Pseudohalides

There are three different ways to convert halogens to alkyl halides or "pseudohalides". Some work better under certain conditions.

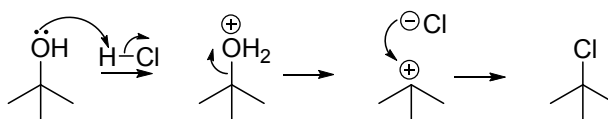
1. React with HX – this looks a lot like $\text{S}_{\text{N}}1/\text{S}_{\text{N}}2$, but just like acid-catalyzed elimination, you need to protonate the OH to make it leave.



Since this is under protic conditions, the larger halogens are better at this reaction. This goes by $\text{S}_{\text{N}}2$ for primary alcohols:



It goes by $\text{S}_{\text{N}}1$ for secondary and tertiary. Again, remember to check for carbocation rearrangement if it's $\text{S}_{\text{N}}1$.



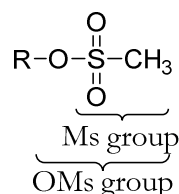
In both cases the ability of the leaving group to detach has some control over the rate of the reaction ($\text{RI} > \text{RBr} > \text{RCl} > \text{RF}$), since it still dissociates during the RDS.

2. The most widely applicable method, and usually the best choice during a synthesis, is to convert the alcohol to a sulfonate ester.

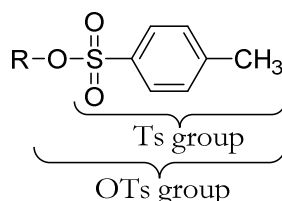
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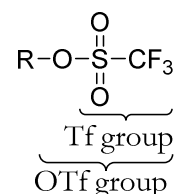
An alkyl mesylate
(methylsulfonate)
contains a mesyl (Ms) group



An alkyl tosylate
(p-Toluenesulfonate)
contains a tosyl (Ts) group

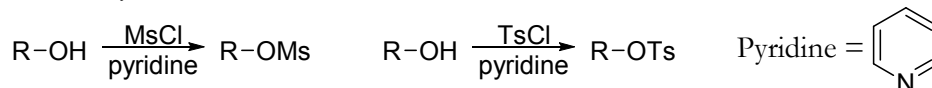


An alkyl triflate
(trifluoromethanesulfonate)
contains a triflyl (Tf) group

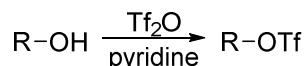


This creates a group that acts so much like a halogen that sulfonate esters are often referred to as pseudohalides. This is because their leaving group ability is about the same as a halogen – the pKa of the $^-\text{OS}(\text{O}_2)\text{R}'$ group is in the same range. Mesyl and tosyl are about as good as bromide, and triflyl is slightly better - about as good as iodide.

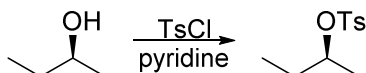
To install mesyl and tosyl groups, you use the acid chloride plus pyridine. Pyridine (often abbreviated as “pyr”) is used to soak up the HCl that gets generated as a byproduct, and because it catalyzes the reaction.



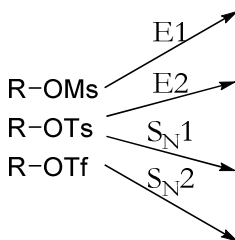
To install the triflate group, you use triflic anhydride (Tf-O-Tf or Tf₂O) plus pyridine again.



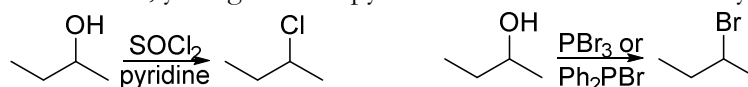
Although we don't look at the mechanism for any of these, it's important to note that the stereochemistry on R will not change during the reaction. The reaction is being done at O, not C.



Once you have any of these three groups in place of the OH group, you can make the molecule do any of the alkyl halide chemistry from Ch. 9, exactly as if it were a real alkyl halide, and following all the same rules about which mechanism is favored when.



3. The third way is to use a special halogenating agent. The two options here are thionyl chloride (SOCl₂) to convert OH to Cl, and either triphenylphosphine dibromide (Ph₃PBr₂) or phosphorous tribromide (PBr₃) to convert OH to Br. The book doesn't cover PBr₃ because it's less popular now, due to being more hazardous and harder to work with. With SOCl₂, you again need pyridine to react with the HCl byproduct.

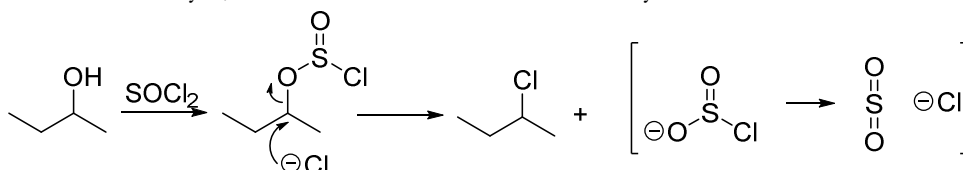


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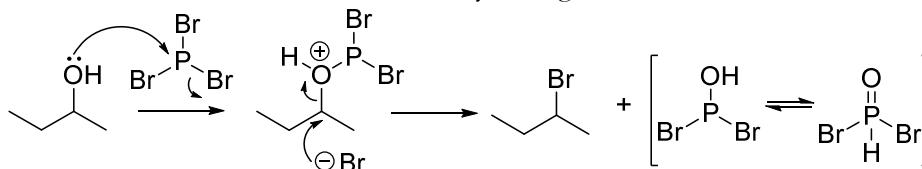
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These are all much better methods than using HX to react with the alcohol. This is partly because they won't react with other functional groups as much – we know HX will react with alkenes to give unexpected products. However, they are more expensive, so sometimes HX is the best choice.

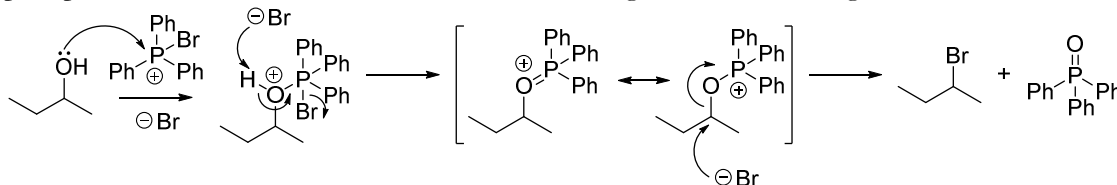
The mechanism for all of these is roughly the same: the OH group attacks the other molecule, causing it to drop a halogen. This halogen then comes in and does S_N2 on whatever group the OH has become. We don't look at the full mechanism of how the OH attaches to the sulfur yet, because it involves S=O chemistry.



For PBr₃, though, the mechanism is basically S_N2 on phosphorous, followed by the bromide leaving group coming back in for an S_N2 on carbon. This creates a species that can rearrange itself to have a P=O double bond, which is very strong and favorable.



Ph₃PBr₂ does something similar, only the bromide is only ionically bonded to phosphorous to begin with the compound exists as a Ph₃PBr⁺ cation, and a Br⁻ anion. Remember that phosphorous can break the octet rule, so even though this looks strange it's still valid.



Since both of these reactions go by S_N2, the end result is inversion of stereochemistry. This also means they work well on primary alcohols and okay on secondary, but not at all on tertiary.



Oxidation and Reduction

In general chemistry and inorganic chemistry, redox (reduction & oxidation) involves the loss and gain of entire electrons. Redox in organic chemistry usually involves the loss and gain of electron density or partial charges. This is tracked by “formal oxidation level” (not the same thing as formal charge). If a carbon atom has bonds to less electronegative atoms like hydrogen, then it has partial negative charges and is **reduced**. If it has bonds to more electronegative atoms like oxygen, then it has partial positive charges and is **oxidized**. Remember, “LEO says GER” – **L**oss of **E**lectron density is **O**xidation, **G**ain of **E**lectron

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density is **R**eduction. Or can also remember “OIL RIG” – **O**xidation Is **L**oss, **R**eduction Is **G**ain.

We can informally categorize functional groups based on how many bonds the carbon has to atoms more electronegative than itself. All the halogens, plus oxygen and nitrogen, are more EN than carbon; most other atoms are less EN.

0 bonds to more EN atoms: CH_4 $\text{H}_3\text{C}-\text{CH}_3$

1 bond to more EN atoms: $\text{H}_3\text{C}-\text{OH}$ $\text{H}_3\text{C}-\text{Br}$

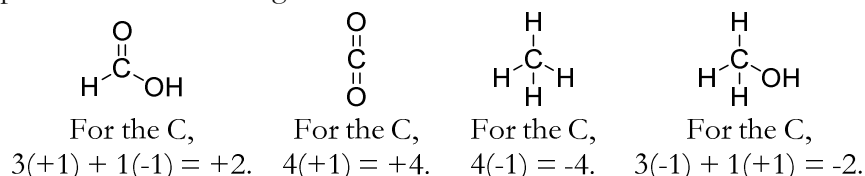
2 bonds to more EN atoms: $\begin{array}{c} \text{O} \\ \parallel \\ \text{H}-\text{C}-\text{H} \end{array}$ $\begin{array}{c} \text{H}_2 \\ | \\ \text{Cl}-\text{C}-\text{Cl} \end{array}$ $\begin{array}{c} \text{H}_2 \\ | \\ \text{HO}-\text{C}-\text{OH} \end{array}$

3 bonds to more EN atoms: $\begin{array}{c} \text{O} \\ \parallel \\ \text{H}-\text{C}-\text{OH} \end{array}$ $\begin{array}{c} \text{O} \\ \parallel \\ \text{H}-\text{C}-\text{Cl} \end{array}$ $\begin{array}{c} \text{O} \\ \parallel \\ \text{H}-\text{C}-\text{NH}_2 \end{array}$ HCCl_3

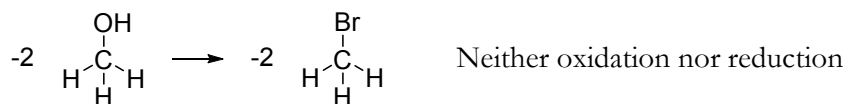
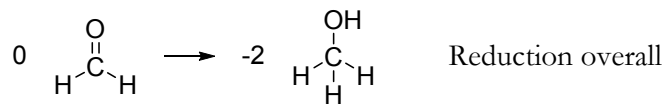
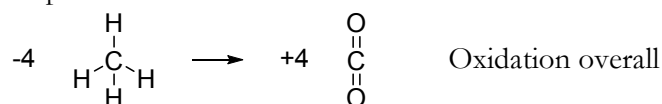
4 bonds to more EN atoms: $\text{O}=\text{C}=\text{O}$ CCl_4

We also have a more formal system to track partial charges on atoms, called “formal oxidation level.” To find the formal oxidation level of an atom:

1. For every bond an atom has to a less electronegative atom or negative charge, add -1.
2. For every bond an atom has to an equally electronegative atom or radical, add 0.
3. For every bond an atom has to a more electronegative atom or positive charge, add +1.
4. Sum up these numbers for a given atom to find its oxidation level.



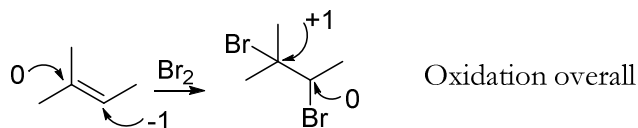
We can track changes on a particular atom or atoms during a reaction, to see whether the molecule as a whole is getting oxidized or reduced. The formal charge of carbon is given below for each product or reactant.



We can revisit some of the reactions we’ve seen previously to sort them into categories of oxidation, reduction, or neither. In this case, you need to sum up the changes across all affected carbons:

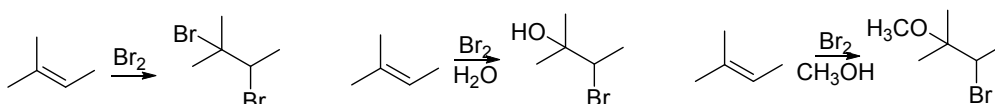
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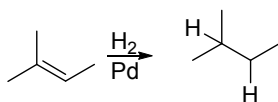


Out of all the alkene additions we've seen, the ones that add 2 non-H groups were all oxidations, the ones that add 2 Hs were reductions, and the ones that add 1 H and 1 non-H were neither.

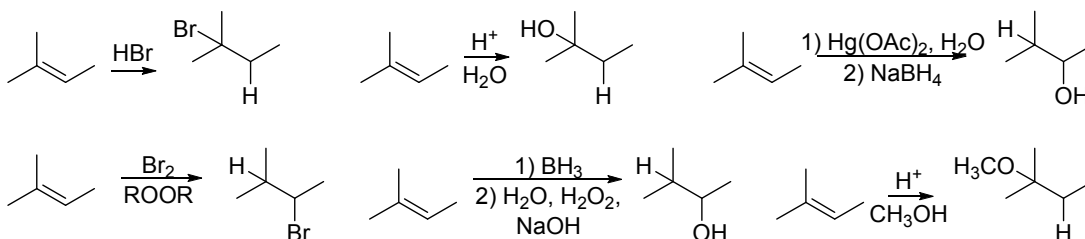
Oxidation:



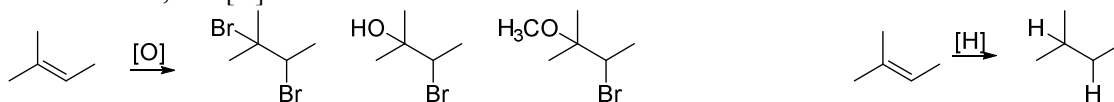
Reduction:



Neither:

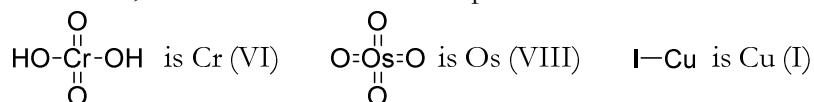


A general way to show that an oxidation or reduction occurs is to put "[O]" above the arrow for oxidation, or "[H]" for reduction.



Typical oxidizing agents contain high-electronegativity atoms, often bonded to each other or to a central, octet-breaking atom. Some examples are Br_2 , H_2O_2 , CrO_3 , and O_3 . Typical reducing agents contain low-electronegativity atoms, often bonded to each other or to a central, low-electronegativity atom. Some examples are H_2 , BH_3 , and NaBH_4 .

As a side note, the net oxidation or reduction must be conserved across all species during a reaction. If an alkene gets oxidized, it is because the other reagents were reduced during the reaction or vice versa. Many transition metals can exist in various different oxidation states, so to specify which it is, we use roman numerals in parentheses after the atom.

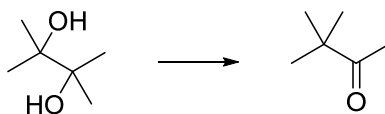


If a reaction uses Cr (VI) and produces Cr (III), we know that the chromium got reduced and so the organic molecule must have been oxidized. Since chromium's formal charge changed by 3, this would be called a "three-electron redox reaction", even though no electrons are being transferred individually.

Often, even if we don't know much about what reagents to use to perform a mechanism, we can narrow it down based on whether it's a reduction, oxidation, or neither. For example, this reaction, called the pinacol rearrangement, is neither overall:

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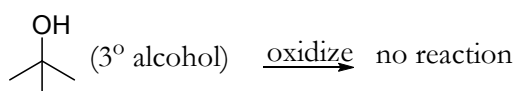
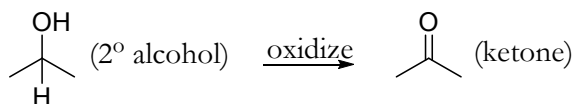
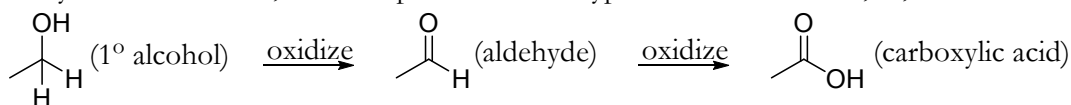
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That means that neither oxidizing agents nor reducing agents are likely to make this happen. In fact, in this case, strong acid is enough to cause it to occur.

Oxidation of Alcohols

This involves changing the oxidation level of the carbon that has the OH on it, by adding more bonds to O. To do this, the C has to lose bonds to H to make room. (In a few cases, it can also lose bonds to C, but aside from one case – ozonolysis – we won't see any reactions like this for a while.) The ability of the C to get oxidized is therefore dependent on how many Hs it has to lose, which depends on what type of alcohol it is - 1°, 2°, or 3°.

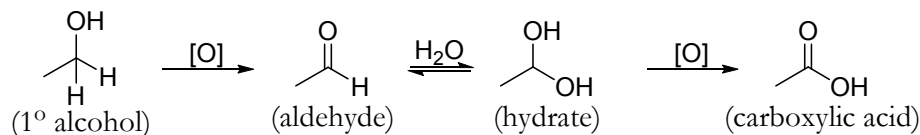


There are two options available for oxidizing agents.

1. Strong oxidizers: for this, you can use most versions of chromium (VI) attached to oxygens, in the presence of strong acid and water. Chromate (H_2CrO_4 or $\text{Na}_2\text{CrO}_4/\text{H}_2\text{SO}_4$), dichromate ($\text{H}_2\text{Cr}_2\text{O}_7$ or $\text{Na}_2\text{Cr}_2\text{O}_7/\text{H}_2\text{SO}_4$), or chromium trioxide ($\text{CrO}_3/\text{H}_2\text{SO}_4$) will work. Potassium permanganate (KMnO_4) will also work but it's harsher and sometimes produces unwanted side reactions. These strong oxidizers will all oxidize up the molecule as far as possible: 1° alcohols will become carboxylic acids and 2° alcohols will become ketones.



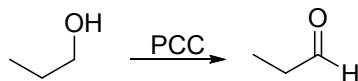
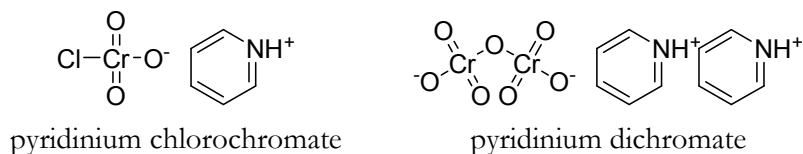
It's hard to stop at the aldehyde state, because if there's water present a side reaction will happen: the molecule will interconvert rapidly between an aldehyde and a hydrate. This hydrate acts just like a regular alcohol and gets oxidized further, to the carboxylic acid state.



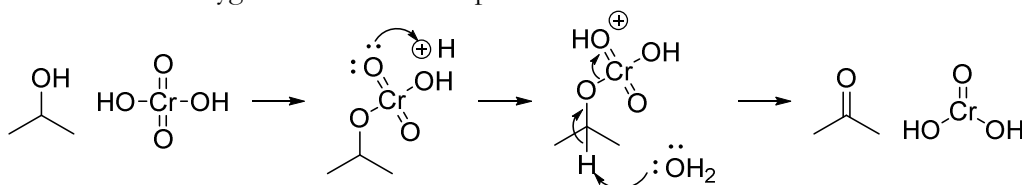
2. Weaker oxidizers: if you want to stop at the aldehyde state, you need to use special chromium (VI) reagents that work in the absence of water. These commonly use DCM as a solvent. The most common one is pyridinium chlorochromate (PCC), but pyridinium dichromate (PDC) works fine too.

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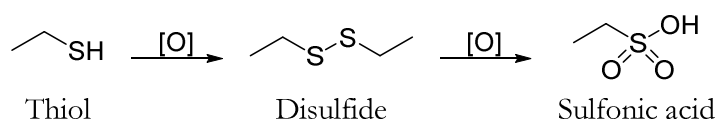


The mechanism is similar for all of these oxidizers: the oxygen forms a bond to the central atom (we won't cover the mechanism for this step), and then something deprotonates the carbon next to the oxygen in an E2-like step.

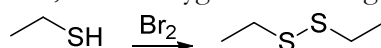


Oxidation of Thiols

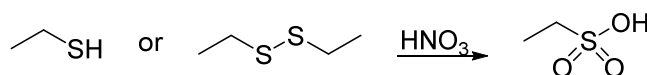
This is different from oxidation of alcohols, because instead of oxidizing C by taking away Hs, we're actually oxidizing S by making it break the octet rule. There are several different oxidation states available to sulfur, but we only look at three of them – thiols, disulfides, and sulfonic acids.



To oxidize a thiol to a disulfide, we can use a very mild oxidizer like Br₂ or I₂. This also happens very slowly in ambient air, due to oxygen itself being an oxidizer.

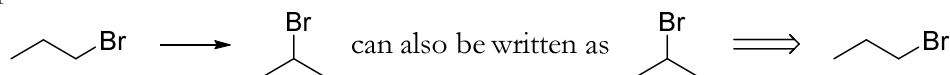


To oxidize a thiol or a disulfide to a sulfonic acid, we need a much stronger oxidizer like HNO₃ or KMnO₄.



More Organic Synthesis

There are some conventions we haven't yet covered. All synthetic routes involve getting from a **starting material** to a **target molecule** or **synthetic target**. We've already seen a few examples where it's easiest to work backwards from the target – this is called **retrosynthetic analysis**. Often this is shown with a two-line retrosynthetic arrow, which basically means "is synthesized from" and can also be shown by a regular arrow pointing in the opposite direction.



Another thing that's helpful for synthesis is keeping track of all the functional group interconversions. Appendix V in Loudon has a good listing of which reactions we can use to get to and from a given functional group – this is a good place to review the methods we've covered so far.

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Finally, one more convention: the “cut here” or “disconnect” line – shown as either a slightly wavy line or a straight line with a knob at each end. This can be used in either the forward or the backwards direction.

