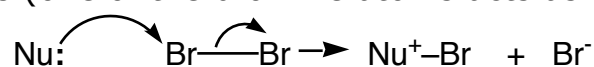
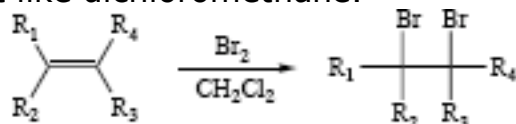


10.1. Addition of X_2 to Alkenes and Alkynes to give 1,2-Dihalides.

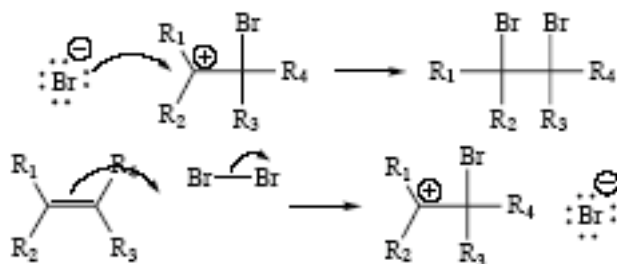
We have mentioned that alkenes and alkynes are not sufficiently good nucleophiles to react with alkyl halides. However, they are sufficiently good nucleophiles to react with elemental halogens, X_2 . Elemental halogens are fundamentally electrophilic: the two electronegative elements are both tugging on the electrons in the σ bond. However, the bond does not break spontaneously to give Br^+ and Br^- , because the former is a very high-energy species (an electron-deficient electronegative atom). Instead, a nucleophile attacks Br in Br_2 directly. Since each Br already has its octet, the Br-Br bond must break at the same time as the new bond to the nucleophile forms (one of the bromine atoms acts as a *leaving group*).



Alkenes react with Br_2 and Cl_2 to give 1,2-dihaloalkanes, or 1,2-dihalides. This addition reaction is usually carried out in a non-nucleophilic solvent like dichloromethane.

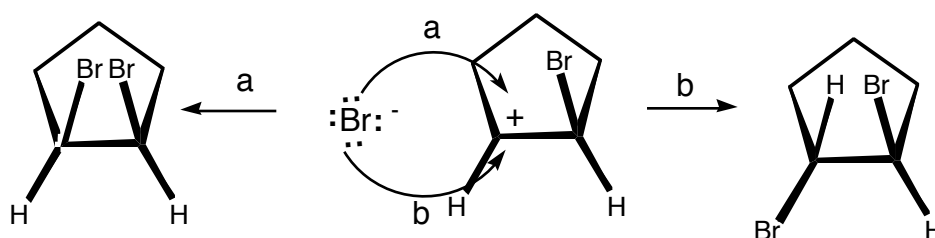
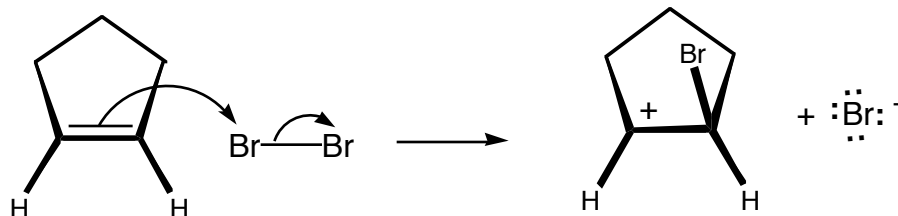


We can think of the reaction following a mechanism similar to the one we discussed for addition of a strong acid to an alkene: the alkene attacks one Br in Br_2 , just the same as alkene attack on H^+ in HBr . Once attack occurs, a carbocation and Br^- is generated. Then Br^- , a nucleophile, adds to the carbocation to give the observed product.



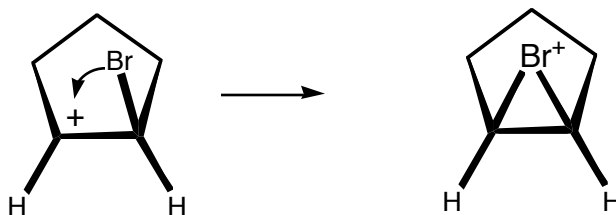
We can get information about whether mechanisms are correct by considering the experimentally observed regioselectivity and stereoselectivity of the reaction and seeing whether the proposed mechanism explains these aspects of the reaction correctly or at all. In the present reaction, since we are adding the same group to both atoms of the double bond, we needn't consider regioselectivity. How about stereoselectivity? Let's see what product we get from the reaction of cyclopentene with Br_2 . In the first step we would get a carbocation with a Br atom on the neighboring carbon. This

carbocation could combine with Br^- to give two possible diastereomers. The Br^- could attack from the same face of the ring as Br resides to give a *cis*-product, or it could attack from the opposite side to give a *trans* product. Since a Br atom is larger than a H atom, we would expect to get more *trans* than *cis*, but not a whole lot more.



In fact, we get exclusively *trans*. Our mechanism doesn't explain this fact. How can we modify the mechanism so that it explains it? It turns out that we had an incorrect structure for the intermediate carbocation.

Imagine the Br atom in the carbocation reaching over and forming a bond to the electron-deficient carbon atom using one of its lone pairs. This gives a three-membered ring called a *bromonium ion*.

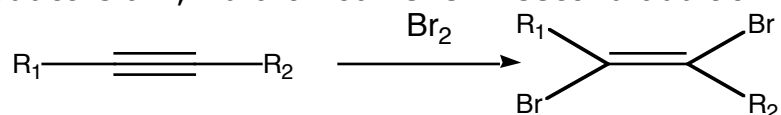


(See **Jones Figs 10.12-10.13**. Also note that the bromonium ion and the 2-halocarbenium ion are structural isomers, not resonance structures, since they have different atom-to-atom connections.) The Br atom has a formal positive charge. The C atom is no longer electron-deficient, but it is still electrophilic, because the Br^+ atom, which is electronegative, wants to leave and have its lone pair back to itself again. The Br^- comes along and attacks the C atom; as its electrons come in to the C atom, other electrons must leave so that the C atom doesn't gain more than an octet; the ones that leave are in the $\text{C}-\text{Br}^+$ bond, which go back to Br. The Br^- attacks from *opposite* the bond that breaks. We obtain *trans*-1,2-dibromocyclohexane as product. This is called overall *anti* addition, because the two Br atoms

add to opposite sides of the double bond. An acyclic substrate will also undergo *anti* addition.

In the example of bromine addition to cyclopentene, we can see that Br^- can attack at either carbon of the bromonium ion intermediate (above). Since the bromonium ion is achiral and the product is chiral, the product is obtained as a racemic mixture. One enantiomer is obtained from attacking one C of the bromonium ion, and the other is obtained from attacking the other C. One synthetic use of the halogenation of alkenes is that the products can be converted to alkynes by two elimination reactions. Thus, alkynes can be prepared from alkenes by a two-step sequence: halogenation, then elimination.

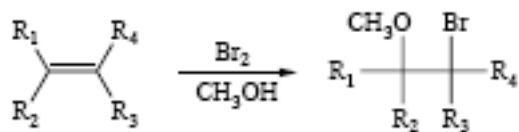
Alkynes also react with X_2 . As in the case with alkenes, the overall addition is *anti* with the halogen atoms trans to one another and the product is a 1,2-dibromoalkene. A second addition can follow



to give the tetrahalide (see Jones fig 10.74).

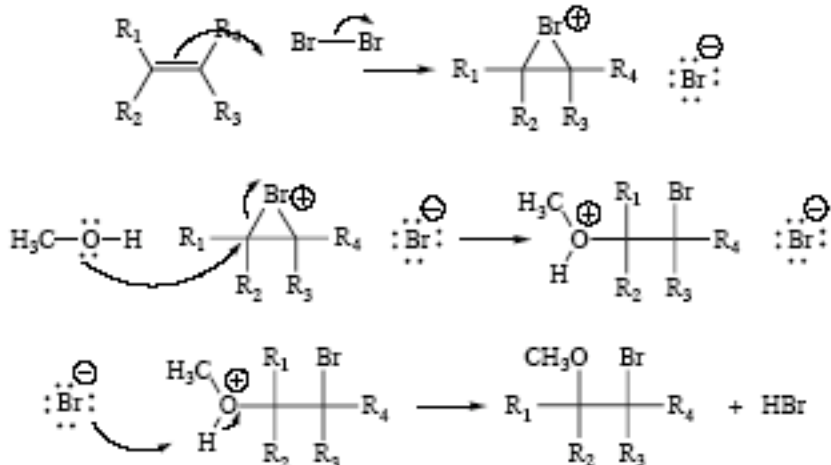
10.2. Coohalogenation. 2-Haloalcohols, 2-Haloethers.

So far we've seen nucleophilic Br^- attack the electrophilic bromonium ion to give a dibromide. Any other nucleophile that is present might also attack the bromonium ion to give a different product. This addition reaction is called *cohalogenation*. Coohalogenation is most commonly conducted by adding Br_2 to an alkene in water, an alcohol, or a carboxylic acid as solvent. For example, if we add Br_2 to an alkene in methanol, we obtain a product in which a CH_3O^- group is incorporated into the product instead of a Br^- group. This product is called a 2-bromoether.

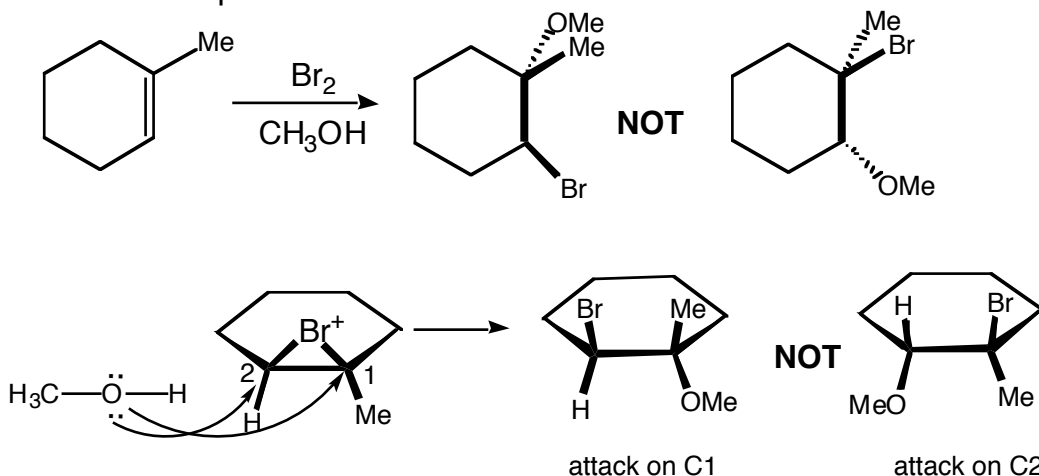


The first part of the mechanism is the same as halogenation; a bromonium ion is formed. Then, instead of Br^- acting as a nucleophile toward the bromonium ion, the alcohol solvent acts as a nucleophile by using its oxygen to attack C and displace Br^- to give a cationic, electron-saturated intermediate. Finally, the oxonium ion intermediate is deprotonated to give the product.

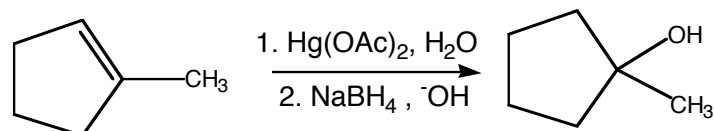
Mechanism:



When we make 2-haloethers and 2-haloalcohols, we are adding one group to one of the C atoms of the double bond and a different group to the other. The question of regioselectivity now arises. For example, what happens if we use 1-methylcyclohexene as a substrate? Remember that we said that 3° carbocations were more stable than 2° ones. We can imagine that in the bromonium ion, the C1-Br⁺ bond is weaker than the C2-Br⁺ bond, because C1 is better able to bear a positive charge. Since the C1-Br⁺ bond is weaker, this bond is more prone to cleavage. Therefore MeOH attacks C1, Markovnikov addition takes place, and the product is 1-bromo-2-methoxy-2-methylcyclohexane (the second one as drawn). Note that *both* regioisomeric products that might be obtained have Br and OMe in a *trans* relationship.



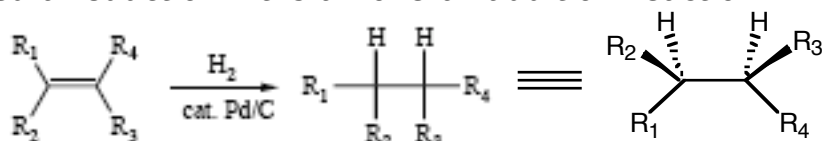
Oxymercuration-Reduction similarly yields alcohols from alkenes via a mercurinium ion and gives the Markovnikov addition product (e.g. see below) - read more about it in your textbook.



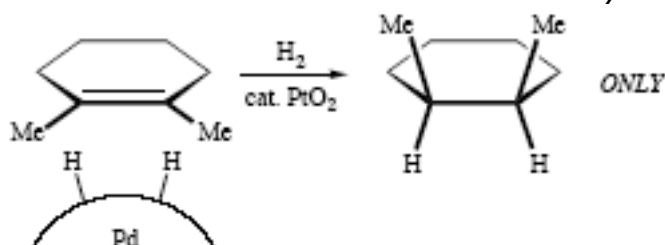
Markovnikov addition product

10.3. Catalytic Hydrogenation. Alkynes to Alkenes to Alkanes.

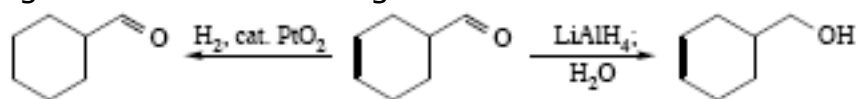
We can hydrogenate alkenes by allowing them to react with H_2 in the presence of a noble metal catalyst like Pd on charcoal (Pd/C) or PtO_2 . This is called a *reduction*. It is an overall *addition* reaction.



Suppose we start with 1,2-dimethylcyclohexene. Two stereoisomeric products are possible: *cis*- or *trans*-1,2-dimethylcyclohexane. In fact, the reaction is stereospecific. Only the *cis* isomer is obtained. Note that the *less* stable isomer is obtained. This is because the mechanism of the reaction does not allow equilibration between stereoisomers. The mechanism of the reaction is beyond the scope of the course. Suffice it to say that in this reaction, the alkene attaches itself to the surface of the metal catalyst (which remains undissolved) and receives both its H atoms from the same face. This is called *syn* addition.



Catalytic hydrogenation is a useful reaction because it usually reduces only *unpolarized* π bonds like $C=C$ π bonds. Polarized π bonds like $C=O$ π bonds are reduced with other reagents such as lithium aluminum hydride, $LiAlH_4$. (The reduction of $C=N$ π bonds is intermediate in difficulty and depends partly on the nature of the groups attached to C and N.) This is called *chemoselectivity*. The fact that $LiAlH_4$ reduces only polarized π bonds and H_2/Pd reduces only unpolarized π bonds means that a compound that contains both of these kinds of functional groups can be selectively transformed into two different products, depending on the choice of reagent.



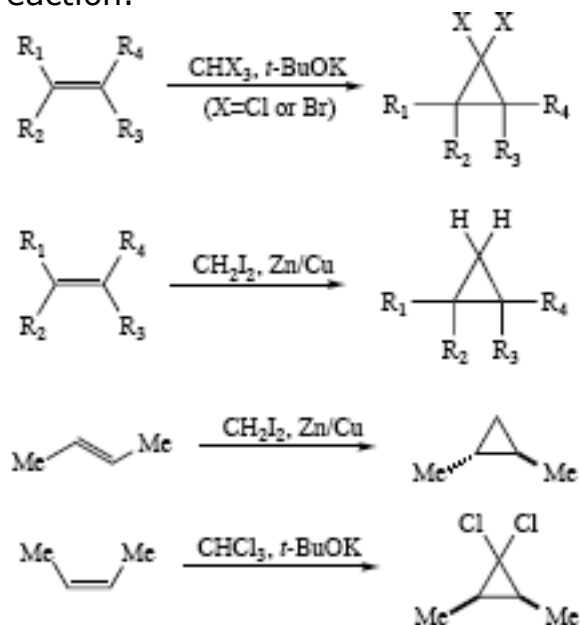
Catalytic hydrogenation has often been used to determine how many of the degrees of unsaturation of a compound with a given formula are due to the presence of $C=C$ π bonds, since cycloalkanes don't react

with H₂. E.g., if the compound C₆H₁₀ (two degrees of unsaturation) reacts with 1 equivalent of H₂, it must have one ring and one π bond.

Alkynes can also be catalytically hydrogenated. Addition of H₂ across an alkyne gives an alkene. We know that alkenes can be reduced to alkanes, so it seems that it should not be possible to stop the reduction at the alkene stage, and alkynes should be reduced directly to alkanes. This is true if a catalyst such as Pd/C is used. However, the second π bond in an alkyne is higher in energy than the first π bond, so if a weaker catalyst is used, the reaction can be stopped at the alkene stage. The catalyst best used is Lindlar catalyst, which is Pd contaminated with Pb (Pd/CaCO₃/Pb). Syn addition of the two H's to the alkyne is observed; i.e., a *cis* alkene is obtained (see Jones figure 10.82).

10.4 Cyclopropanes from Alkenes. Carbenes.

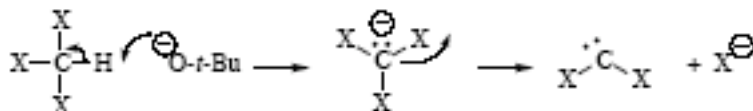
We can synthesize cyclopropanes from alkenes. There are two major ways to do this. First, we can use chloroform or bromoform (CHX₃, X= Cl or Br) and potassium *t*-butoxide (a strong base) or 50% aqueous KOH to generate an unstable intermediate called a *carbene* that adds to the alkene to give a 1,1-dihalocyclopropane. Alternatively, we can use CH₂I₂ and Zn with a little bit of Cu in it (so-called Zn/Cu couple) to generate a *carbenoid* compound, the Simmons-Smith reagent, that adds to the alkene to give a cyclopropane. Both of these result in an overall addition reaction.



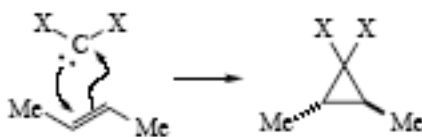
These reactions are *stereospecific*. A *cis* alkene gives a *cis* cyclopropane, and a *trans* alkene gives a *trans*-cyclopropane. There are no regiochemical issues.

Let's discuss the first reaction first. With all of the electron-withdrawing groups on the central C atom in CHX₃, the C–H bond is

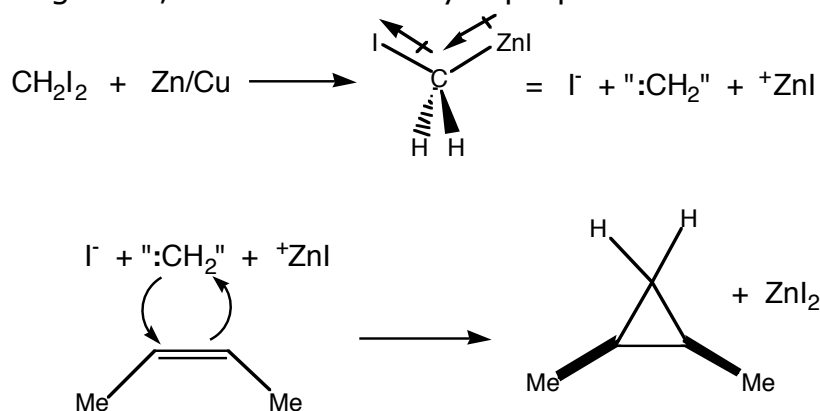
rather acidic ($pK_a = 15$, almost the same as $H_2O!$). A strong base like $t\text{-BuOK}$ can deprotonate it to give a *carbanion*, a trivalent C species with a negative charge. C is a somewhat electropositive element, and it doesn't like to bear a negative charge. To relieve this charge, one of the X groups attached to C can leave as X^- with the electrons in the C–X bond. The C species that is left behind is a divalent, six-electron species called a *carbene*. (In this case, a dihalocarbene.)



As you might imagine, carbenes are extremely reactive species, even more reactive than carbocations. Since they are electron-deficient, they chomp on anything with a pair of electrons. They react with the π bond of alkenes in a pericyclic (no intermediate) reaction. The pair of electrons in the π bond goes to form a bond between C_{carbene} and C1 of the alkene, while the lone pair on C_{carbene} goes to form a bond between the C_{carbene} and C2. The reaction is stereospecific, with *trans* alkenes giving *trans*-1,2-disubstituted cyclopropanes.

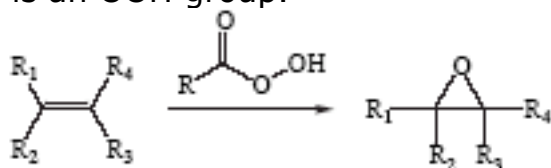


The Simmons-Smith reagent works similarly. The Zn inserts into one of the C–I bonds to give a compound with a C–Zn bond. The C–Zn bond is heavily polarized with a δ^- on C, so you can imagine that I^- might leave from C (just like in the formation of a dihalocarbene). This isn't exactly what happens, which is why we call the Simmons-Smith reagent "carbenoid", which is a metal-complexed reagent with carbene-like reactivity. Thus, the Simmons-Smith reagent reacts with alkenes more or less in the same way as a true carbene does. The product is a cyclopropane. The reaction again is stereospecific, with *cis* alkenes giving *cis*-1,2-disubstituted cyclopropanes.

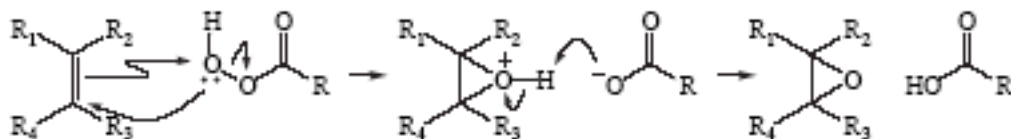


8.10. Oxidation of Alkenes. Epoxides, 1,2-Diols, Carbonyls.

When alkenes are treated with a peracid, RCO_3H , an epoxide is obtained. The peracid used most often in the lab is called *m*-CPBA, but any peracid, even peracetic acid, AcOOH , will work. A peracid is related to a carboxylic acid, but instead of an OH group attached to the carbonyl there is an OOH group.

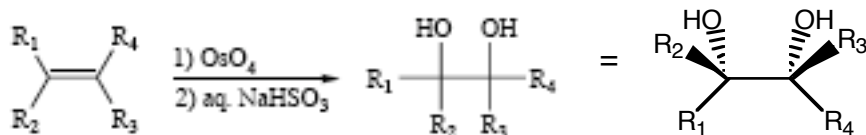


Alkenes are nucleophiles, so peracids should be electrophiles. In fact, as in Br_2 , the two electronegative O atoms are fighting over the pair of electrons in the σ bond between them. The CO group attached to one O helps it win the battle, so the O atom attached to H is even more electron-poor. The alkene attacks it, displacing a carboxylate anion, and the O being attacked uses its lone pair to make a bond back to one of the alkene C's to give a protonated epoxide. The carboxylate then deprotonates the O to give the products.

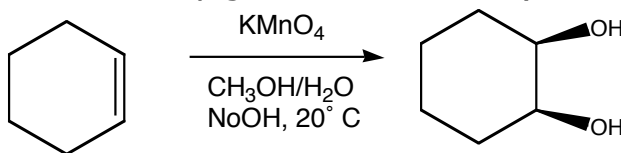


We will now learn two other *oxidation* reactions whose mechanisms are too complex to discuss. You must simply memorize these reactions. It is important to learn them because they accomplish useful functional group transformations.

When alkenes are treated with one equivalent of OsO_4 (osmium tetroxide) and then aqueous NaHSO_3 , a 1,2-diol is formed. This reaction is called *dihydroxylation*. The overall reaction is an addition reaction.

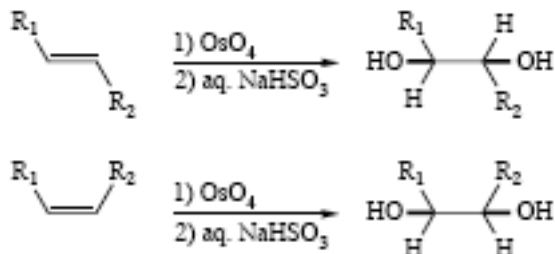


Basic permanganate similarly gives vicinal diols (1,2-diols)



There are no regiochemical issues in dihydroxylations, because the same group is added to each atom of the former π bond. The

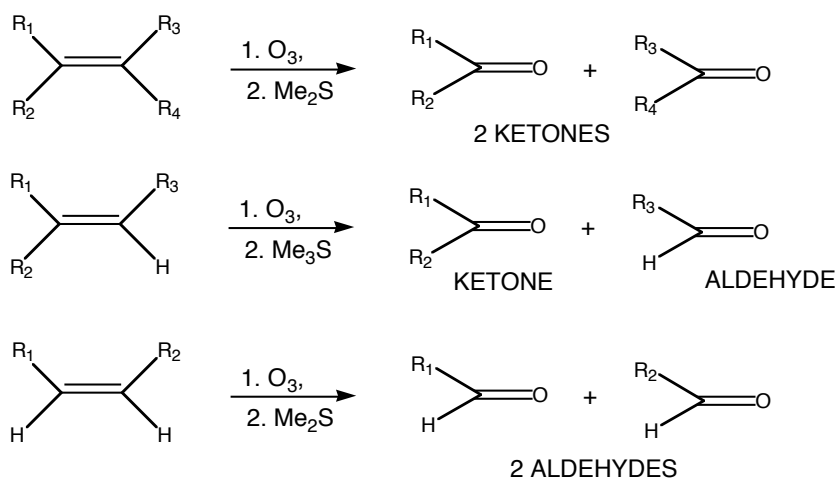
stereochemistry of the reaction is stereospecifically *syn*; both OH groups add to the same side of the double bond. Only the *cis* diastereomer is obtained from a cyclic substrate. A *trans* alkene gives a single diastereomeric product; the corresponding *cis* alkene also gives a single product, different from the one derived from the *trans* alkene.



This reaction is very mild, very selective for C=C bonds, and proceeds in high yields. The problem with it is that OsO₄ is extraordinarily toxic and volatile (evaporates easily). To get around this problem, we usually use a *catalytic* amount of OsO₄ in conjunction with a stoichiometric amount of another oxidizing agent that regenerates OsO₄ after it has reacted and allows it to react again. Also, people generally run the oxidation in the presence of pyridine, because it goes faster under these conditions. For our purposes, though, stoichiometric OsO₄ without pyridine is just fine for making 1,2-diols.

The C=C double bond in alkenes can be *oxidatively cleaved* and replaced with two C=O double bonds. This can be done in several ways. We will learn only one: ozonolysis. When an alkene is treated with ozone, O₃, and then a mild reducing agent such as Me₂S (reductive work-up), two ketones or aldehydes are obtained. Other reducing reagents besides Me₂S can be used, e.g. Zn, Ph₃P, and even H₂ and a catalyst.

reductive work-up

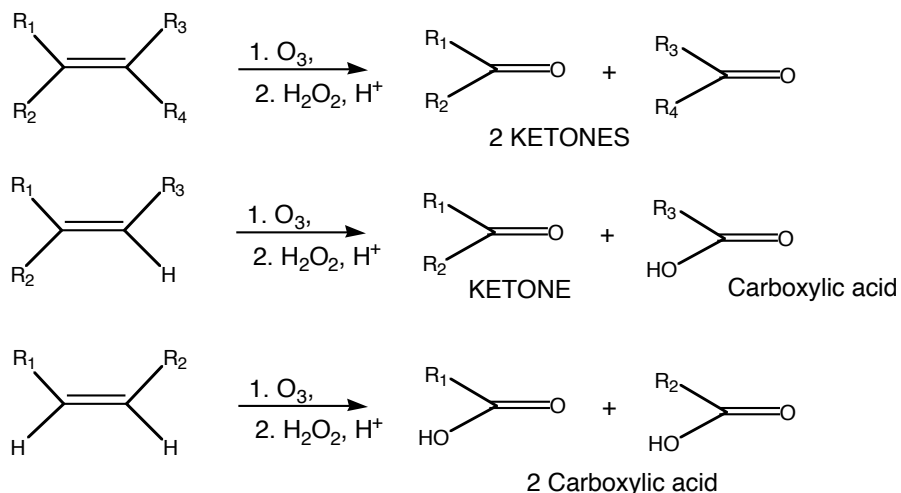


R = alkyl

See Jones Figure 10.62

Oxidative work-up with H_2O_2 leads either to ketone or carboxylic acids:

oxidative work-up



R = alkyl

The mechanism of this reaction is well-known, and it is in the book if you are interested, but I do not expect you to know it. Oxidative cleavages of alkenes have neither regiochemical nor stereochemical issues.