Reactions of Alkenes

Alkene Electrophilic Addition Reactions

Most of the chemistry of these unsaturated hydrocarbons consists in the addition of X-X or X-Y molecules. All reactions are driven by the fact that the two newly formed σ bonds are stronger than the π bond and the X-Y σ bond. Throughout the discussions of the addition reactions, pay attention to the following issues:

(1) **Timing**: Is the addition concerted or not. If not, what type of **intermediate** occurs.

(2) **Regiochemistry**. If the alkene is asymmetric, which part of the reagent X-Y goes to which C-atom of the multiple bond?

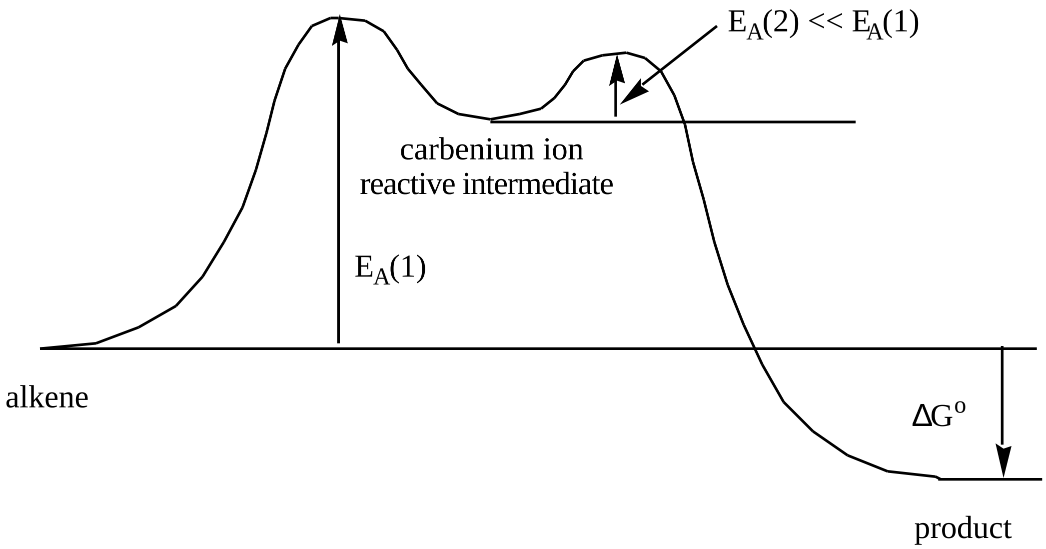
(3) **Stereochemistry**.
The alkane formed may have chiral centers.

HX Additions Involving Hydrogenhalides

HX gas is bubbled through a solution of the alkene and alkyl halides are obtained. The acid HX first protonates to yield a **carbenium ion** intermediate. Then, in the next step, the halide ion is added to the carbenium ion. The proton is an electrophile, so we call this an electrophilic addition reaction because the electrophile adds in the slow step.

Potential Energy Diagram for the Addition Reaction

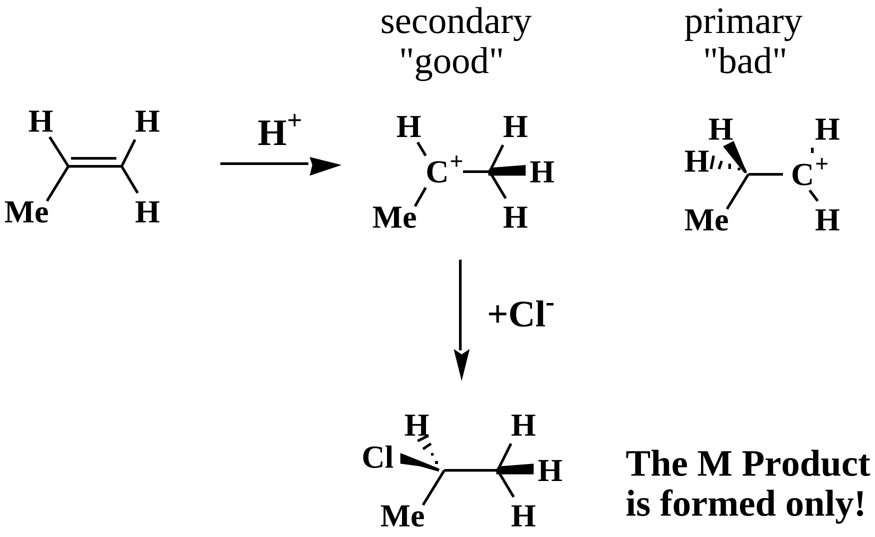
Electrophilic addition is a **two-step process** where the first step is the slow step.



Regiochemistry

Markovnikov's Rule: The protonation occurs at that C-atom of the unsymmetrical double bond that already has more H-atoms attached. **Hydrogen to hydrogen!** The reason for the M-rule is simple: You want to form the more stable, more substituted carbenium ion intermediate! This is all you need to know about the regiochemistry of HX addition.

Example: HCl addition to propene.



The M Product is formed only!

A chiral C-atom is formed in the process. This chiral C-atom will be **racemic** because the intermediate is planar and can be attacked from either face with equal probability.

Anti-Markovnikov Products: If the HX is added with the opposite regiochemistry, that is, when hydrogen adds to the higher substituted C-atom of the double bond, then we refer to this addition product as the anti-Markovnikov product.

This happens when the mechanism of the addition is not a polar mechanism but a radical mechanism instead. The important point to remember here is this:

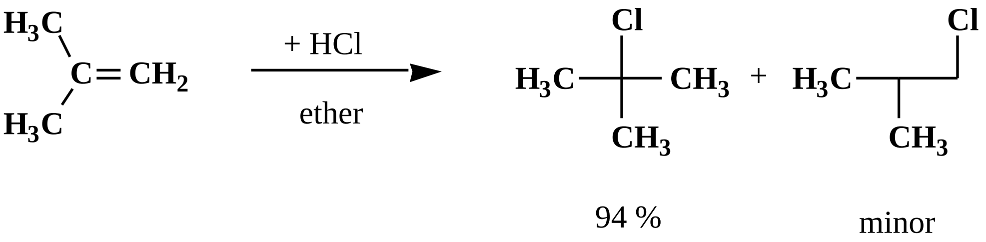
(a) **Initiation:** ROOR yields RO• radicals
    RO• radical reacts with HX to give ROH and X•
(b) **Propagation**:
    Step 1: X• adds to alkene to give the more stable radical
    Step 2: The alkyl radical abstracts H from HX.
(c) **Termination**: Any pair of radicals combines.

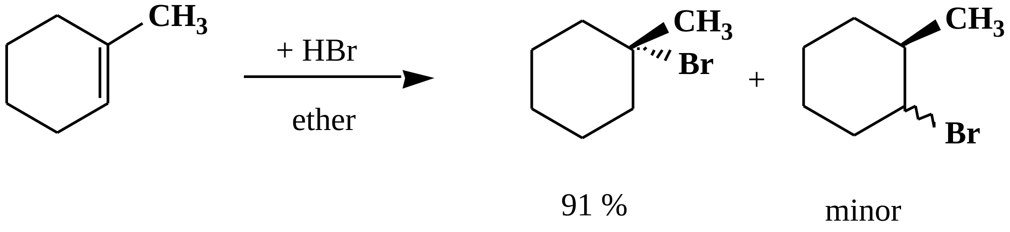
Regiochemistry of HX Addition

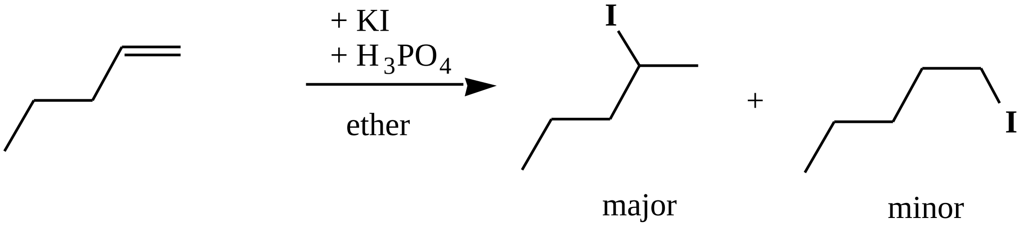
Electrophilic additions via most stable carbenium ion
give Markovnikov Product
Radical additions via most stable radical
give Anti-Markovnikov Product

Examples

Note the regiochemistry in each case. Note that HI additions usually are not done directly with HI but instead the HI is produced *in situ* from KI and H_3PO_4. The solvent is given either over or (more often) under the reaction arrow. Make sure you would be able to name all of the molecules in these examples.





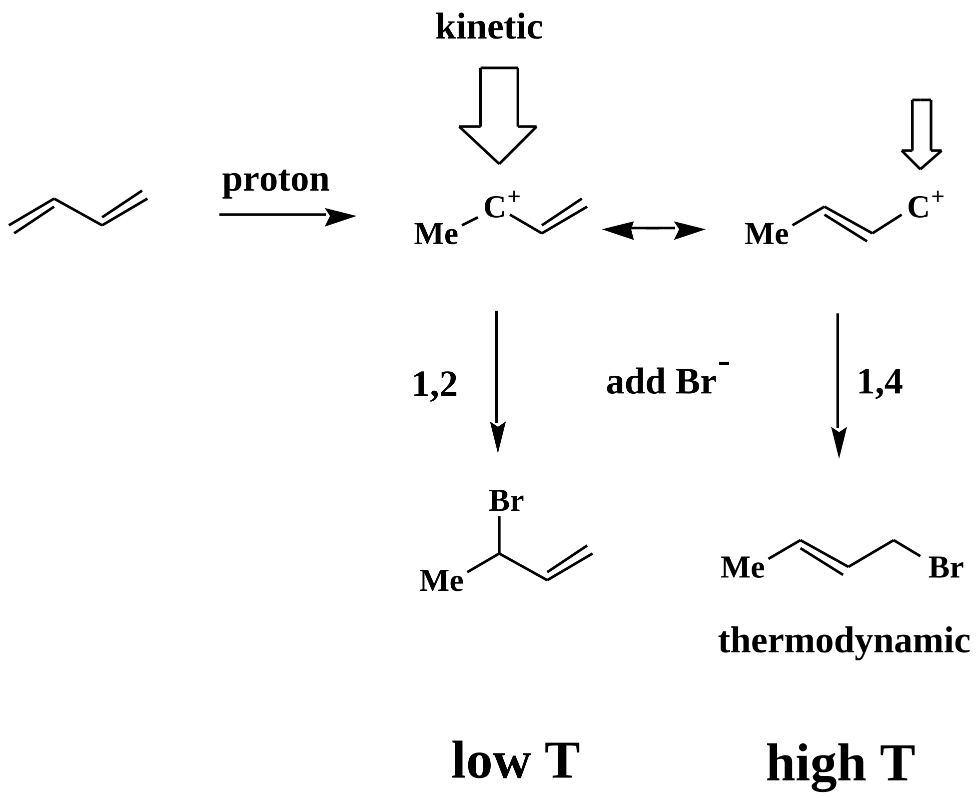


HX-Additions of Dienes: 1,2- or 1,4-Additions

In the electrophilic additions to dienes we get **allylic systems**. These allylic system **can be attacked by a nucleophile at two places**. Thus, one can get two products in which the remaining double bond is at different places. Which one of the products is preferred depends on the reaction conditions.

Low T => 1,2 addition AND High T => 1,4 addition
Traces of acid favor 1,4 addition

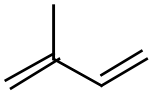
Example 1: 1,3-butadiene and HBr.



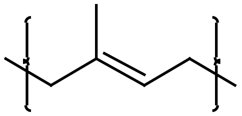
1,4-Additions in Polymerizations of Dienes

Example 1 Polyisoprene - Electrophilic Polymerization

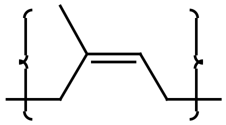
Catalytic (acid cat.) polymerization of isoprene leads to natural rubber. In rubber the remaining double bonds are all *cis*. If they are all *trans*, then the material is hard and called gutta-percha (golf ball coverings).



isoprene
2-methyl-1,3-butadiene

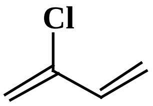


gutta-percha

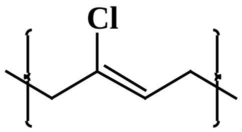


rubber

Example 2: Neopren - all *trans* head-to-tail 1,4-polymer of 2-chloro-1,3-butadiene.



2-chloro-1,3-butadiene



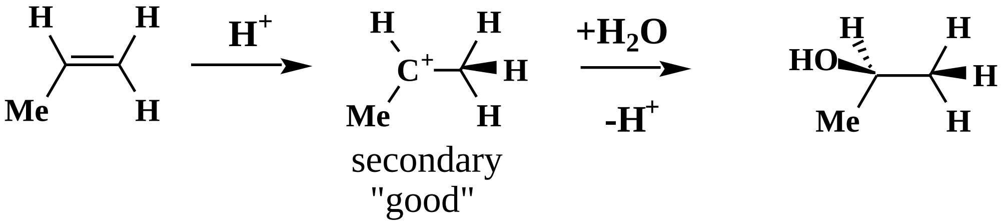
neopren

More on polymers in Chapter 26 … but not now.

Hydration: H_2O Additions to Alkenes

The hydration of alkenes yields alcohols. It is just the opposite of the formation of alkenes from alcohols. Which direction does go then? It depends on the experimental setup. If we take measures to get the water out of the reaction mixture (excess concentrated acid), then one gets the alkene, and otherwise (excess water) one gets the alcohol.

Example: 2-propanol



The hydration requires acid catalysis. A dilute acid is used (HCl, HBr, H_2SO_4).

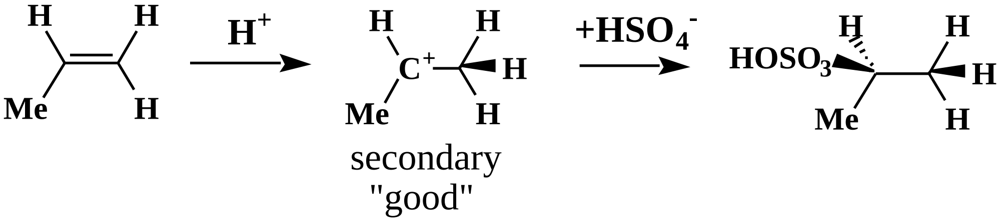
Markovnikov rules!

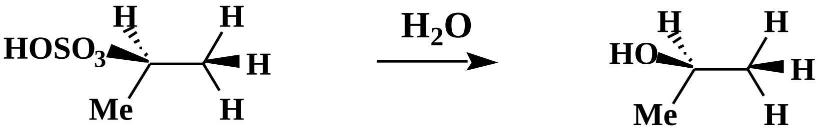
Disadvantages: Alkenes usually are not very soluble in water. Poor reactions with low yields.

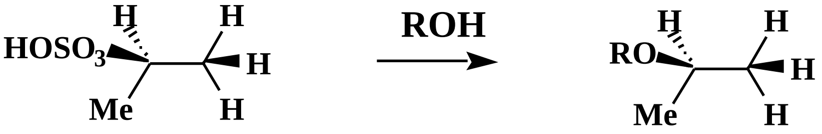
Indirect Hydration via Sulfates: H_2SO_4 Additions.

Same mechanism as discussed for the electrophilic HX addition. The addition of sulfuric acid to alkenes is a route to **inorganic esters**. Alkenes dissolve in concentrated sulfuric acid and react in high yield to form bisulfates (or hydrogen sulfate). These bisulfates can then be used in S_N2 reactions to form ethers and alcohols simply by boiling in alcohols or water.

<u>Example 1:</u> 2-propyl hydrogen sulfate







Indirect Hydration: Oxymercuration & Hydroboration

Oxymercuration-Demercuration: Addition of mercuric acetate $HgAc_2$ to alkenes yields oxymercurated molecules that can be treated with sodium borohydride and water to give the **Markovnikov** alcohol from the alkene.

Hydroboration(-Deboration): Reaction of alkenes with boranes yields alkylboranes which can be converted to alcohols with **anti-Markovnikov** regiochemistry in excellent yields!

Major advantage: No rearrangements! Remember that direct hydration involves a carbenium ion and this ion may undergo rearrangements to form more stable carbenium ions before the water is added. Oxymercuration and hydroboration do not give rearranged products.

Remember: Alkenes to Alcohols

(1) HX addition - rearrangements possible - M products

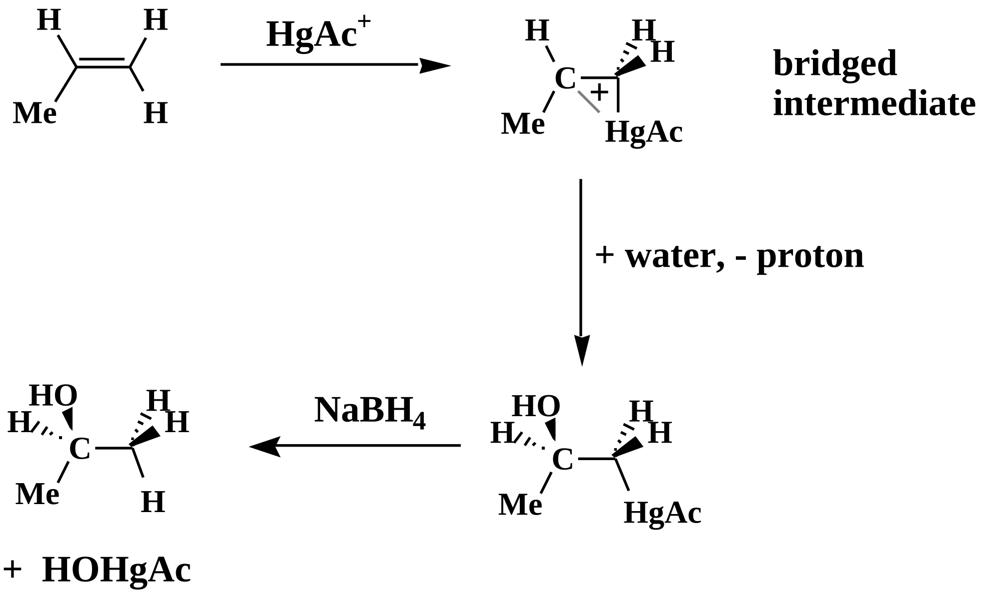
(1) H_2SO_4 addition - no rearrangements - M products

(3) Oxymercuration - no rearrangements - M products

(4) Hydroboration - no rearrangements - AM products

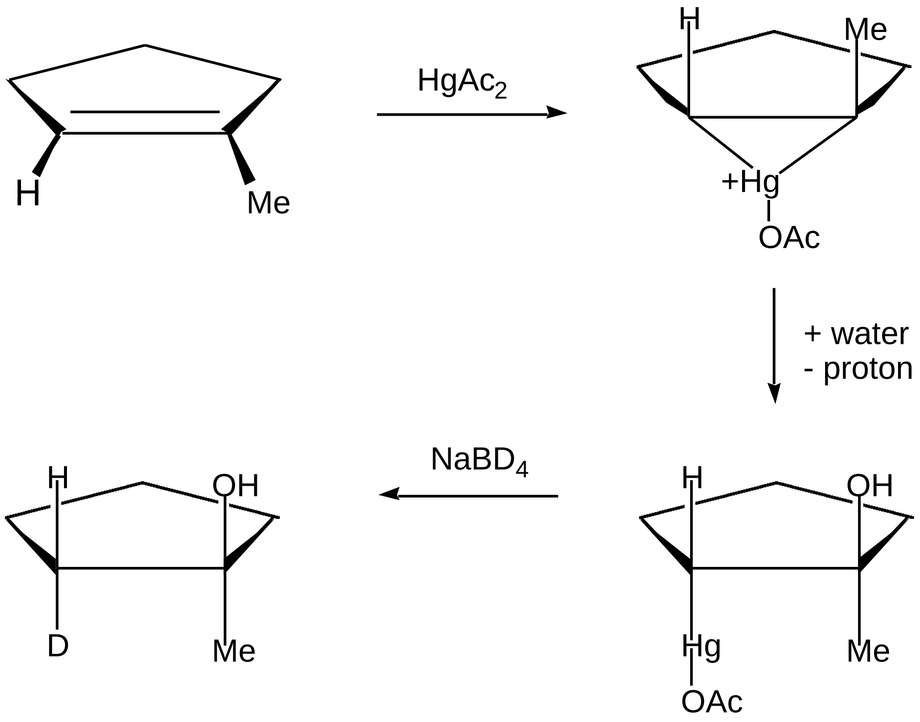
Mechanism of Oxymercuration

The reactive species, $HgAc^+$, is formed by loss of Ac^- from $HgAc_2$. The important point is, that the addition of $HgAc^+$ to the alkene does not give a carbenium ion but that instead a bridged, 3-membered ring cation is formed, **the mercurinium ion**. In the event of rearrangement, this ring would have to be destroyed; that process requires too much energy and rearrangements do not occur. The bridged intermediate is then attacked by water, it loses a proton, and we get the oxymercurated molecule (aka organomercurical alcohol). Reduction with $NaBH_4$ follows. The reduction is worked up with water. Overall, a hydride is delivered to the carbon and a hydroxide is delivered to the metal.



Oxymercuration of 1-Methylcyclopentene

The regiochemistry is Markovnikov and the stereochemistry is *anti* addition, that is, the OH and the introduced H (or D) will be in a *trans* relation with regard to each other.

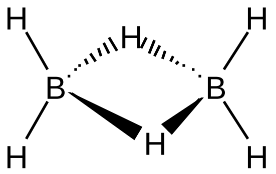


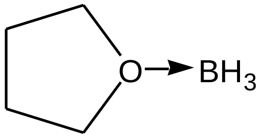
Alkoxymercuration - Demercuration

When the reaction is carried out in an alcohol solvent, then the mercurinium ion adds alcohol to form an ether. Reduction with sodium borohydride then yields an ether.

Mechanism of “Boration”

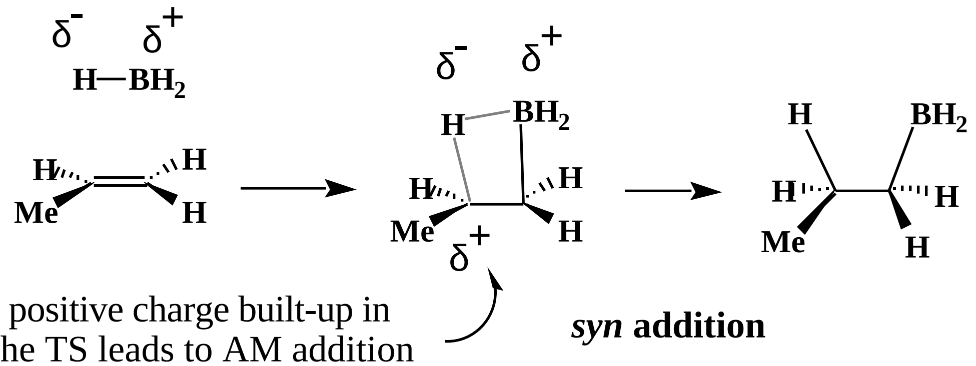
Borane BH_3 dimerizes to diborane B_2H_6. In THF, borane BH_3 forms a Lewis acid/Lewis base complex with THF. Whenever we talk of “borane BH_3,” we really mean this THF complex.





BH_3 has negatively polarized H and a positively polarized B. The B-atom is going to do the electrophilic attack (!) and the **H comes in as an anion** - not as a cation! The rule that governs the regiochemistry is always the same: Make the more stable carbenium-type site in the TS (or the intermediate). The boron adds to the side that has more Hs because that leads to the more stable carbenium-type TS.

The C-H and C-B bond formations occur via a 4-membered ring TS. Both H and BH_2 attack the double bond from the same side: H and BH_2 will always be placed *cis*.

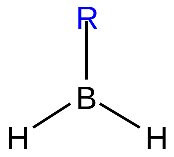


positive charge built-up in the TS leads to AM addition

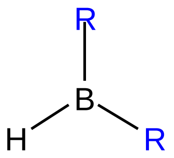
***syn* addition**

Primary, Secondary and Tertiary Boranes

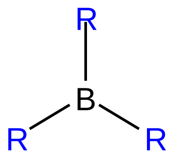
In discussions of mechanisms of hydroboration, the reactions usually are written in a manner that suggests that pimary alkyl boranes R-BH_2 are formed. This is done for simplicity only. In reality, BH_3 will react with three alkenes to form BR_3 and all of the subsequent reactions occur then three times for each BR_3. So instead of the alkylboranes formed, we really do form trialkylboranes.



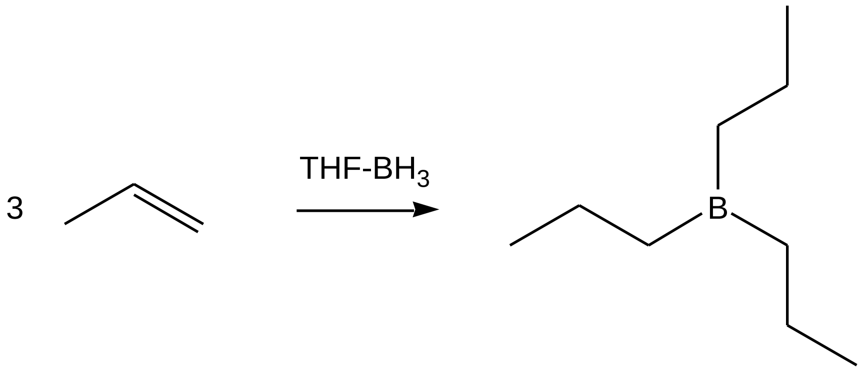
primary
borane



secondary
borane

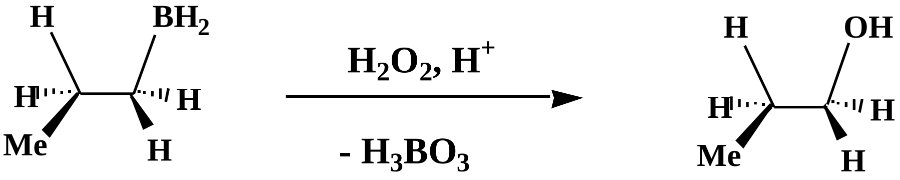


tertiary
borane

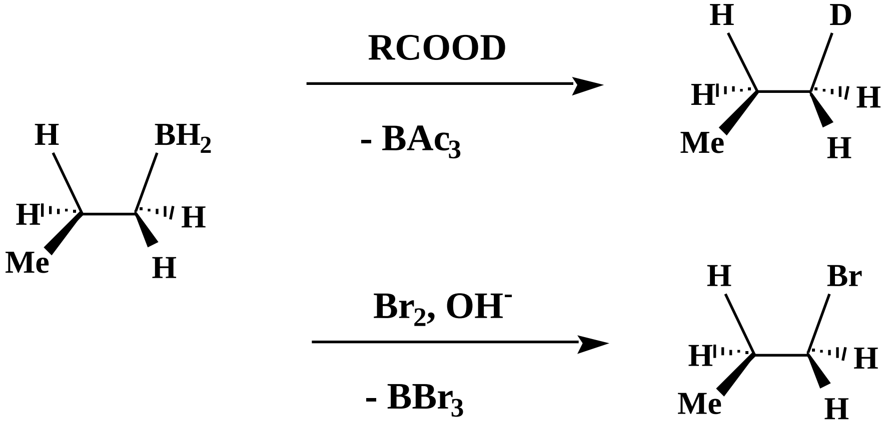


Workup of Alkylboranes

Once the alkylborane is formed, one treats this primary product with hydrogenperoxide/acid to convert to the alcohol. (The C-B bond is broken and OH is added to C and B.) The borane is turned into boronic acid in the process. This process occurs with retention of configuration at the C-B carbon. This is the most usual second step and the boration together with this oxidation is the hydroboration.



The alkyl boranes can also do other reactions. Reactions with acid and with halogen are shown. The first one is a good way to put a D-label in place.

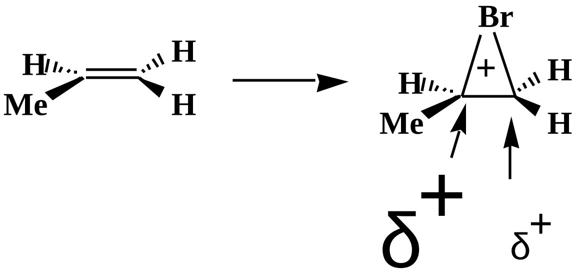


Halogenation of Alkenes

Only important for Br_2 and Cl_2. For F_2, the reaction is too exothermic (explosive!) and for I_2 it is endothermic. Mostly done with bromine.

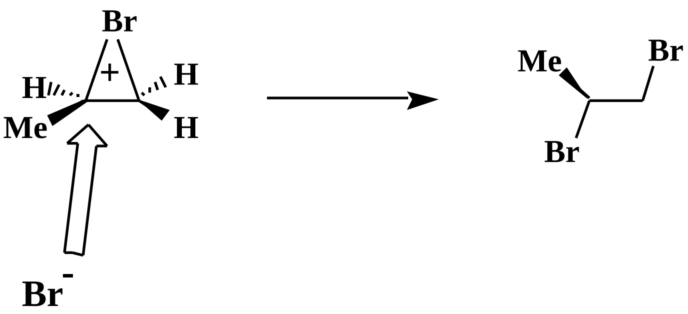
Step 1: Autoionization. Br_2 undergoes **heterolytic** cleavage to Br^+ and Br^-.

Step 2: Br^+ adds to form a cyclic **bromonium ion**.

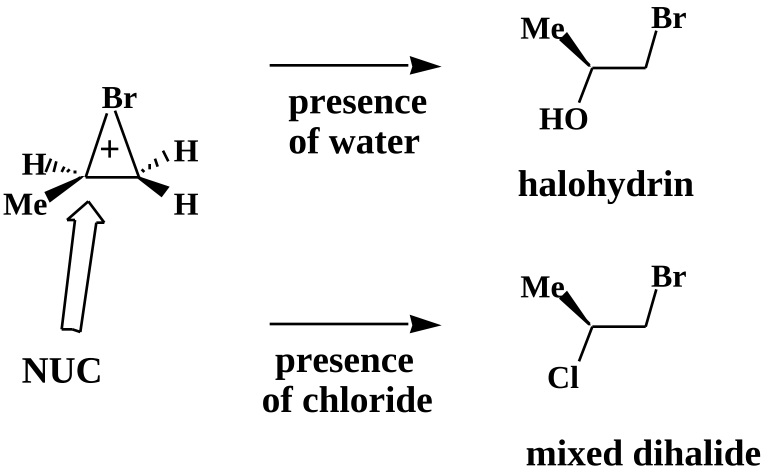


Bridged Bromonium Intermediate

Step 3: Br^- adds from the opposite side to give *trans* addition. The nucleophile cannot attack from the same side as the Br^+ because of the ring formation. The nucleophile will add to the more substituted carbon!



Alternative steps 3: Addition of some other nucleophile present. Again, the nucleophile will add to the more substituted carbon! This is a

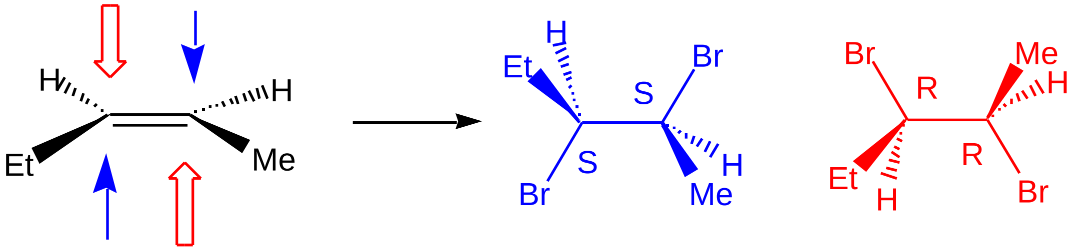


The halohydrin formation is important. When halogantions are carried out in inert solvents (carbon tetrachloride, chloroform), then the only available nucleophile is the halide ion. If the reaction is carried out in a nucleophilic solvent, such as water, then the solvent becomes the most likely nucleophile and halohydrin formation is dominant.

Stereochemistry of Halogenation

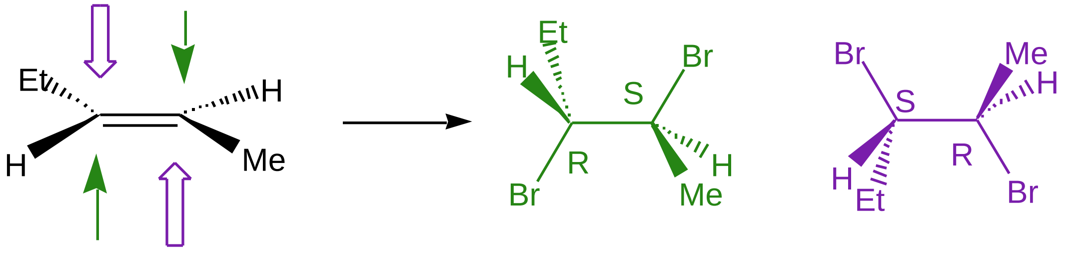
The additions always are *trans*. This also is called *anti* addition. If we do such a *trans* addition for a cyclohexene, then we will form two chiral carbons. If one *trans* addition leads to (*R*,*R*), then the other *trans* addition will lead to (*S*,*S*). That is, we will form enantiomers. Because of the *trans* addition, we will *not* form diastereoisomers. Make sure you get this! We'll talk about this in the review.

<u>Example:</u> Bromination of *cis* (or *Z*) and *trans* (or *E*) 2-pentene



racemate of enantiomers

no diastereoisomers (R,S) and (S,R)



racemate of enantiomers

no diastereoisomers (S,S) and (R,R)

Hydrogenation - Catalytic H_2 Additions

The metal catalyst serves to cleave the H_2 homolytically. H radicals are the reactive species that add to the surface coordinated alkene. Hydrogenations with solid metal catalysts are **heterogeneous** reactions. Hydrogenations with dissolved metal catalysts are **homogeneous** reactions.

Stereochemistry of Heterogeneous Reaction

The two H-atoms most usually add from the same side - *cis* or *syn* addition. This matters (a) in the reduction of cycloalkenes to a,e-cycloalkanes and (b) in hydrogenations of tetrasubstituted alkane that result in two chiral centers.

Typical catalysts are Pt and Pd.

Cheaper metals also can be used but they usually require higher reaction T and p. Unless special precautions are taken, all unsaturations will be removed - complete hydrogenation. The Adams catalyst PtO_2 forms Pt *in situ*. Pd is used as palladium black Pd/C, Pd surface on graphite.

alkene ==> alkane
alkyne ==> alkane
aldehyde/ketone ==> primary/secondary alcohols
nitriles ==> primary amines
aromatics ==> cycloalkanes

Poisoned Catalysts

Such catalysts can be used to reduce alkynes to alkenes without further reduction to the alkane. They consist of a metal catalyst and some added compound. The add-ons are things like quinoline or $BaSO_4$.

Oil and Fat Hardening

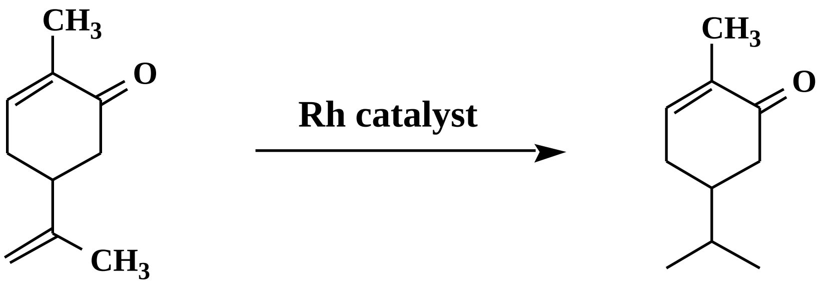
Vegetable oils are liquids (oils!) and that is so because they have many unsaturations in the hydrocarbons of the acids (of the glycerine triester). So, partial hydrogenation reduces the number of these unsaturations and we get margarine (butter is better).

<u>Example:</u> Linoleic acid (C_{18}-acid) is *cis* H_3C-$(CH_2)_4$-CH=CH-CH_2-CH=CH-$(CH_2)_7$-COOR - is reduced with H_2 at Pd/C catalyst to stearic acid.

Homogeneous Hydrogenation with Wilkinson's Catalyst $(Ph_3P)_3RhCl$.

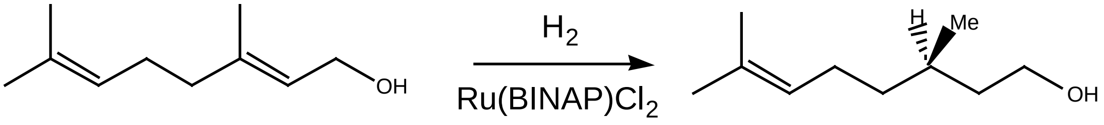
The alkene coordinates to the metal and so does the H_2. The nice thing about these homogeneous catalysts is that the less hindered double bond is reduced preferentially.

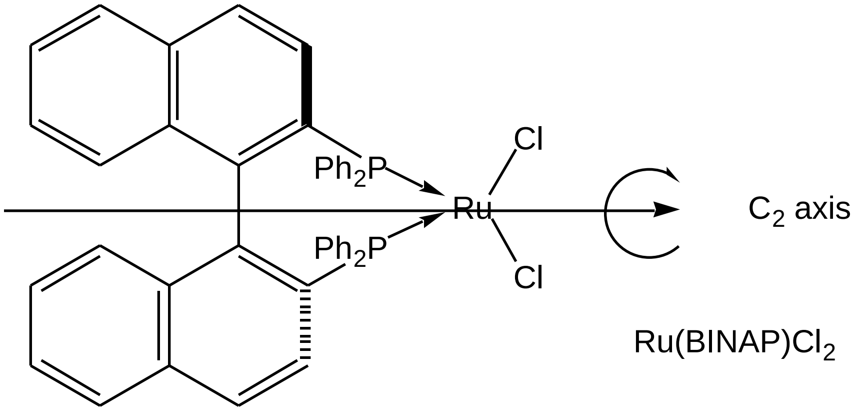
Example:



Homogeneous Hydrogenation with Chiral Induction.

With chiral phosphines the catalytic hydrogenation can be carried out stereoselectively and stereospecifically.





Note also that the carbonyl group was not reduced under these conditions. This is actually one of the excellent features of the catalytic hydrogenation in general: It is quite selective for double bonds and does not reduce polar multiple bonds.

<u>Example 1:</u> Unsat. ketone. 2-cyclohexenone to cyclohexanone

<u>Example 2:</u> Unsat. ester. Methyl 3-phenylpropenoate to methyl 3-phenylpropanoate

<u>Example 3:</u> Unsat. nitrile. Cyclohexylideneacetonitrile to cyclohexylacetonitrile.

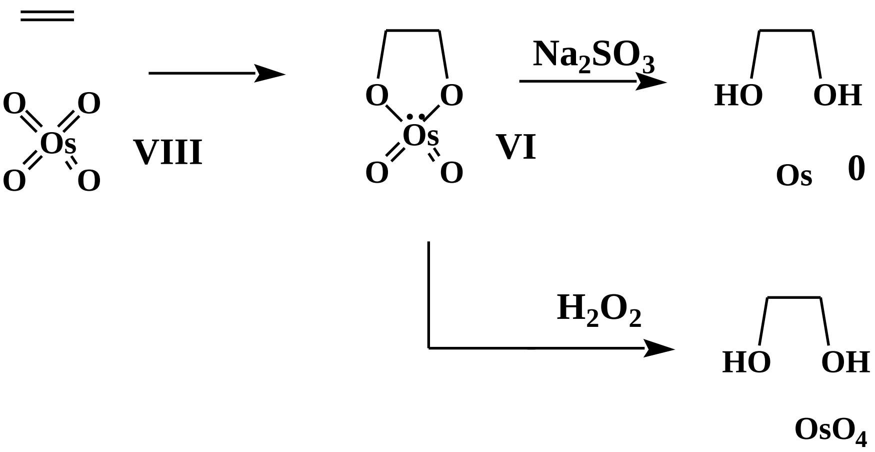
Oxidation of Alkenes

NO CC CLEAVAGE: Epoxides Diols (Glycols) Methyl Ketones
WITH CC CLEAVAGE: Aldehydes Ketones Acids

Oxidations Without CC Bond Cleavage

Diol Formation with OsO_4

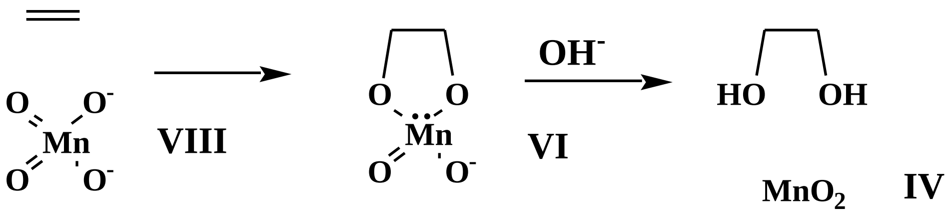
OsO_4, osmium tetroxide (aka osmic acid, toxic, expensive) to give osmate ester. Followed by reduction of the cyclic product with sodium sulfite, $NaSO_3$, or sodium hydrogensulfite, $NaHSO_3$. This workup yields osmium metal. Alternatively, the osmate ester can be treated with hydrogen peroxide. This also give the diol and osmic acid is regenerated.



The diol formed in this way always is a *cis*-diol!

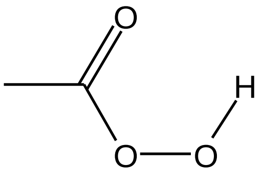
Cold, alk., aq. Sol. of Permanganate. $KMnO_4$/NaOH

This is very much similar to the osmium tetroxide oxidation. This is the **Baeyer Test** for unsaturation. Start with purple solution (permanganate) and get a brown precipitate of “brown stone” (MnO_2).

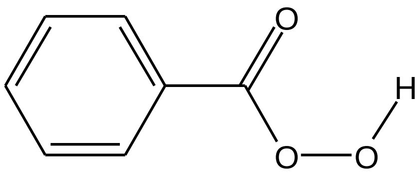


Epoxide Formation

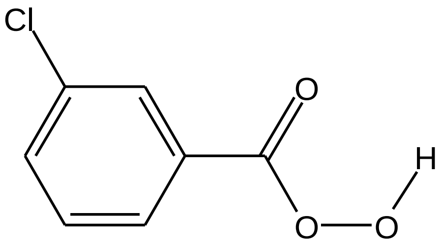
H_2O_2 and carboxylic acid or peroxycarboxylic acids (MCPBA is *meta*-chloroperbenzoic acid) react with alkenes to form epoxides.



peroxyacetic acid

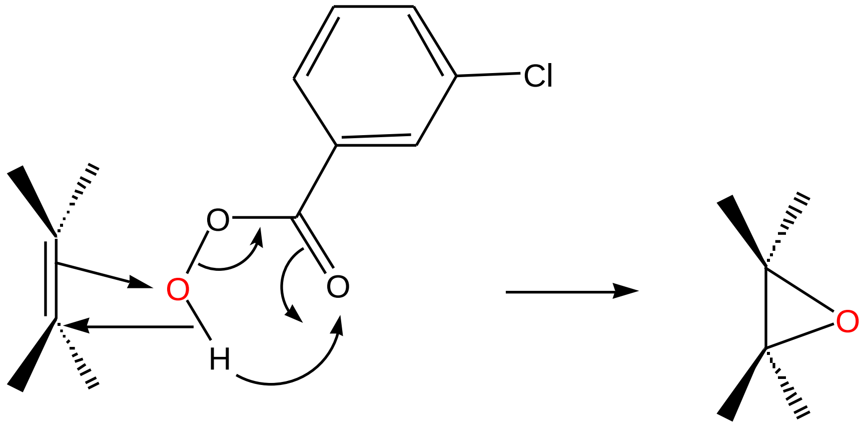


peroxybenzoic acid

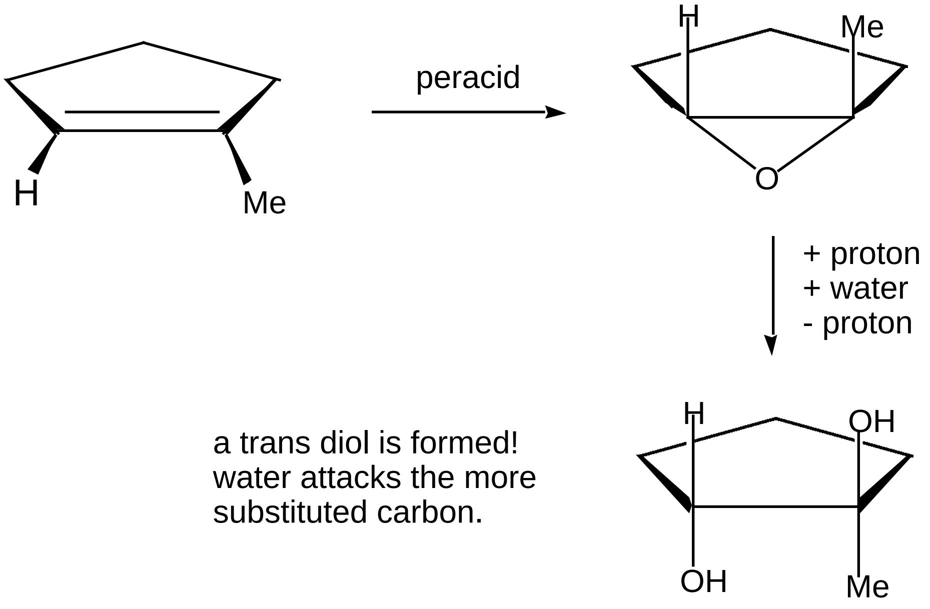


MCPBA
meta-chloroperbenzoic acid

Transition State for Epoxidation



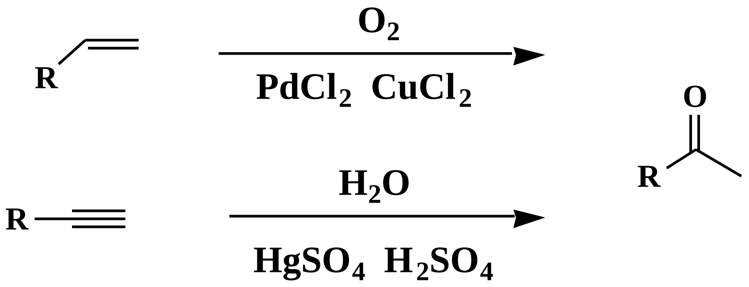
Stereochemistry: Opening an epoxide to form a diol with KOH or such, will form the *trans* diol! This is in sharp contrast to the oxidations with osmium tetroxide and potassium permanganate which give *cis* diols.



a trans diol is formed!
water attacks the more
substituted carbon.

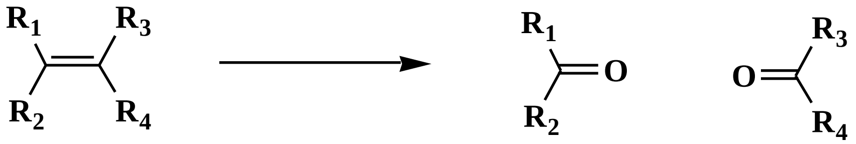
Methyl Ketones from Terminal Alkenes

Oxidation of terminal alkenes with $PdCl_2$ in the presence of $CuCl_2$ gives methyl ketones. This is an alternative reaction to the hydration of the terminal alkynes.



Oxidations With CC Bond Cleavage

Hot Permanganate Oxidation



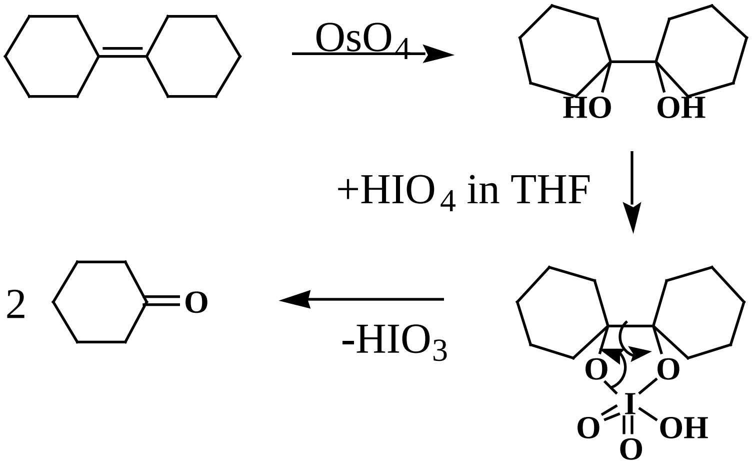
Depending on the nature of the R groups, aldehydes and/or ketones or formed.

If aldehydes are formed, then these may be oxidized further to the acids.

If formaldehyde is formed, then this will be oxidized to CO_2 (via formic acid and carbonic acid).

Oxidative Cleavage of 1,2-Diols

Alkenes can be oxidized with C=C cleavage directly using hot permanganate (above) or ozone (below). In addition, there is an alternative route that works very well, namely the sequence of (1) forming the 1,2-diol with OsO_4 and (2) cleavage of the diol with HIO_4 in THF. A cyclic periodo intermediate is involved.



Ozonolysis

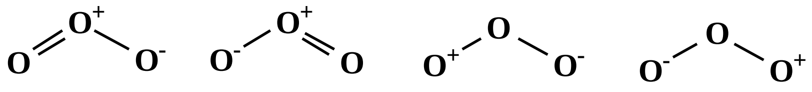
Ozone Depletion. The periodic increase of the sun activity, increased vulcanic activity, and a general alteration of the stratospheric climate have been suggested as possible natural causes. Other hypotheses link the ozone depletion to anthropogeneous causes and, specifically, to organic halogen compounds that form free chlorine radicals. Chlorine, hydroxy radical, and nitroso radical are well known to destroy ozone *via* catalytic cycle. However, the magnitude of the ozone depletion cannot be accounted for by these catalytic cycle alone. Three hypotheses have been suggested to explain the increase of the chlorine concentration.

Hypothesis I: Solomon *et al.* (*Nature* **1986**, *321*, 755) suggested that $ClONO_2$ reacts in a surface catalyzed (clouds) dark reaction with HCl.
Hypothesis II: McElroy *et al.* (*Nature* **1986**, *321*, 759) suggested an ozone decomposition cycle based on Cl and ClO which is made more effective by participation of BrO radicals.
Hypothesis III: Molina *et al.* (*J. Phys. Chem.* **1987**, *91*, 433) have suggested that Cl_2O_2 has to be considered as a possible source of reactive chlorine.

Back to earth. What does Ozone do to alkenes? Here we go:

Criegee Mechanism for Ozonolysis

Ozone

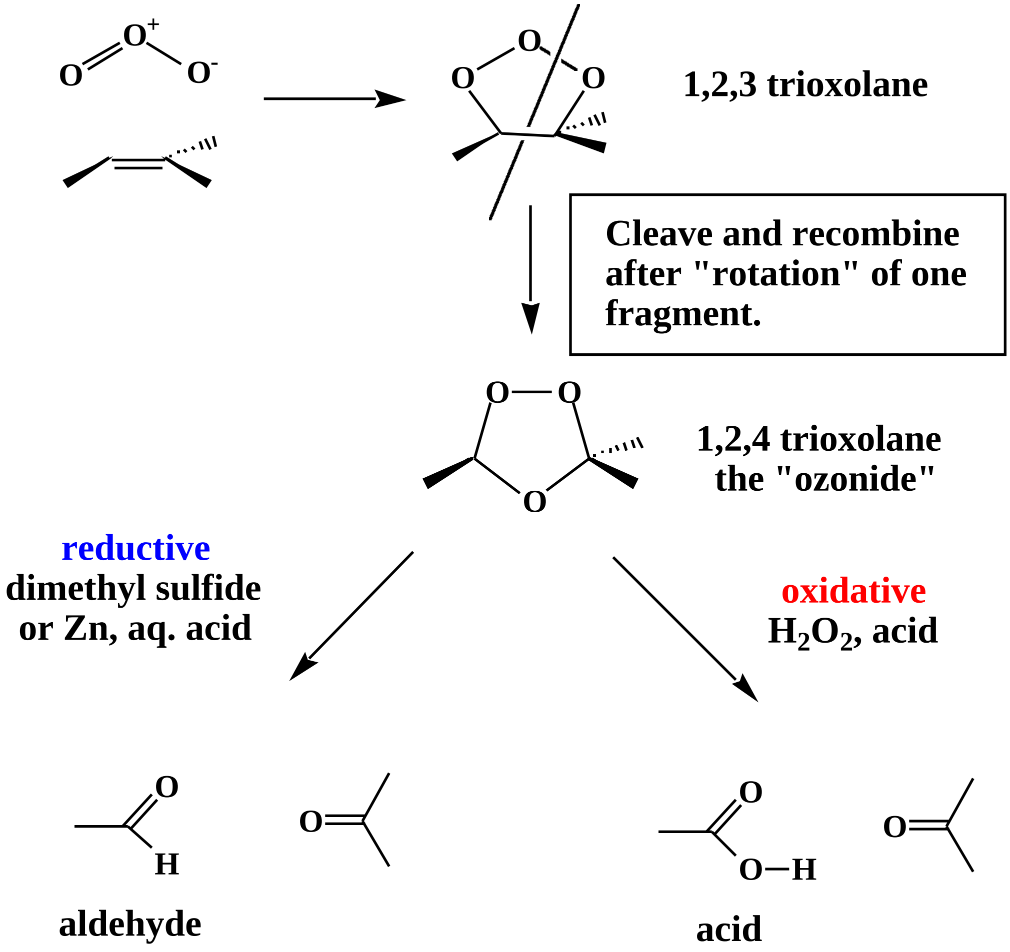


Step 1: 1,2,3-trioxolane formation

Step 2: Cleavage as indicated by dashed line

Step 3: Recombination to form 1,2,4-trioxolane

Step 4: Oxidative (K and acid) or reductive (A/K) work-up.

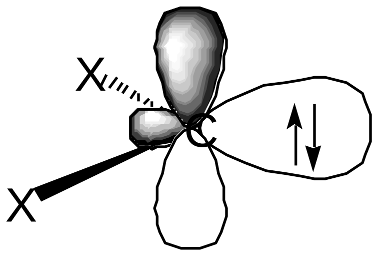


Carbene Additions - Cyclopropane Synthesis

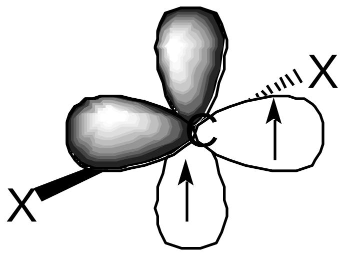
Carbenes are compounds of the type CR_2. Yes, just two groups attached to C and C has a lone pair. R groups can be H, alkyl, aryl, halogens, etc.

Structure of Carbenes

They can be either bent with an sp^2 carbon or they can be close to linear (close to sp hybridization). Note that the book says linear, but recent research shows these species to be not quite linear. The difference between the two is with the electron configuration.



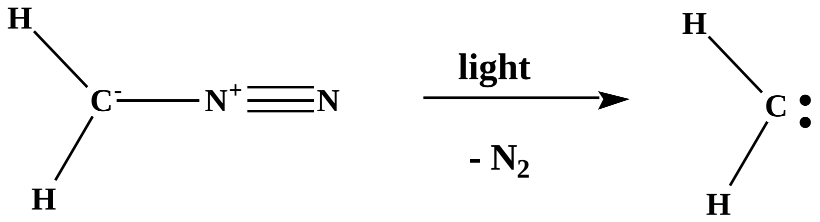
Bent
Singlet Carbene
2 paired electrons
in a σ C-AO



Linear
Triplet Carbene
2 unpaired electrons
in two p-AOs of C

Preparation of Singlet Carbene

Photolysis or Thermolysis of Diazomethane, CH_2N_2



Alpha-Elimination from $CHCl_3$ or $CHBr_3$

This is the way the dichlorocarbene was made first. HCl elimination **from the same C** with strong base KOH yields CCl_2 via K^+ $HCCl_2^-$. Same for $CHBr_3$. Bent structure.

Simmons Smith Preparation of “Carbenoids”

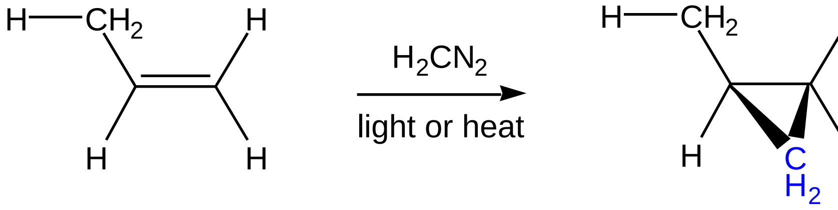
Excellent. Carbenoid because there is no free real carbene, but the reagent reacts just like a free carbene. Diiodides are reacted with Zn in the presence of Cu (zink-copper couple) in ether.

CH_2I_2 + Zn (Cu) --(in ether)--> I-CH_2-ZnI “carbenoid”

Reactions of Carbenes

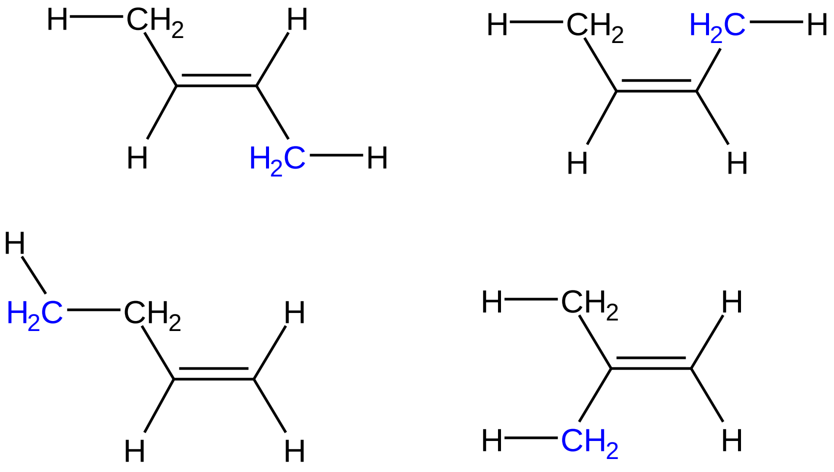
They add to alkenes to form cyclopropanes. The best way to make three-membered rings! The stereochemistry always involves *cis* addition and this *cis* addition can occur from either side. So, we can form pairs of enantiomers but not their diastereoisomers. *Meso* forms are possible. Use the following three examples to review the stereochemistry of rings.

<u>Example 1:</u> Addition of carbene to propene. There also are side-products formed by way of insertion into CH bonds.

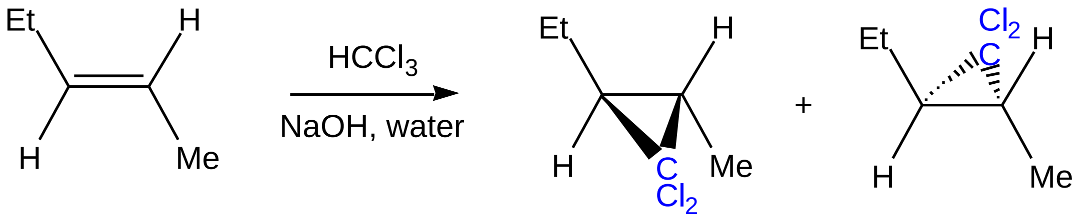


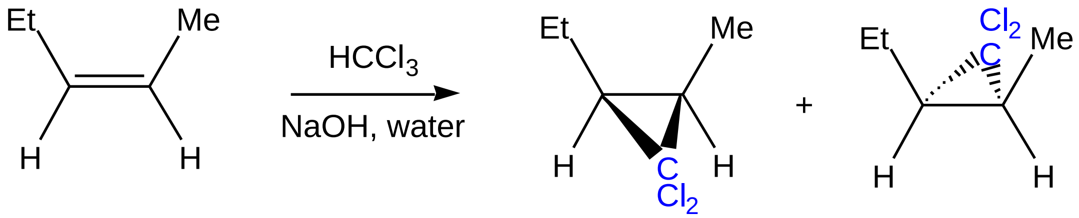
Carbene Addition

C-H Insertion give side products

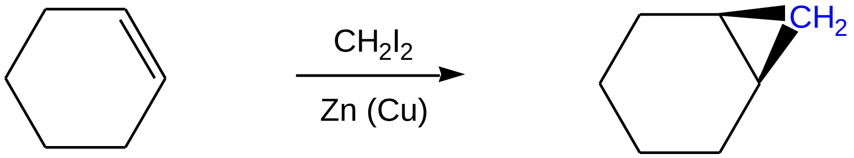


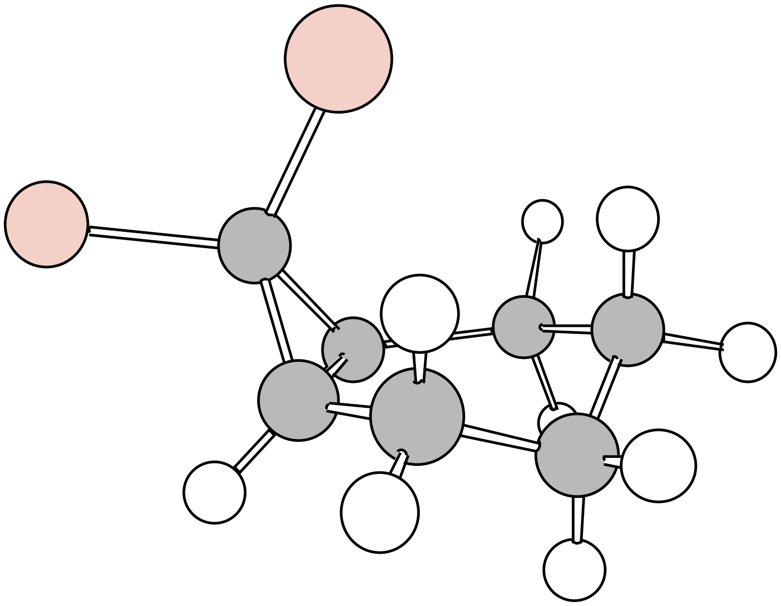
Example 2: Addition of Carbene to *Z*- and *E*-2-pentene.
Pairs of enantiomers are formed. Stereospecific reaction.





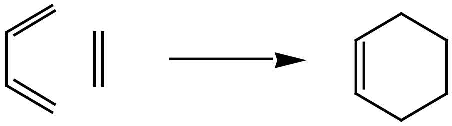
<u>Example 3:</u> *Cis*-Addition of Carbenoid to Cyclohexene.



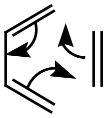


Diels-Alder Reaction (Nobel Prize 1950)

Best method for the construction of 6-membered rings:
Diene plus alkene form a cyclohexene.



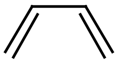
cis diene



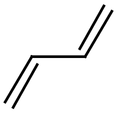
4+2

Diene Conformation

It is important for this reaction that the diene is in the "s-cis" conformation and not in the more stable "s-trans" conformation.



s-cis



s-trans

Substituents on Diene and Ene

(1) The diene wants to be electron-rich (alkyl substituents help)

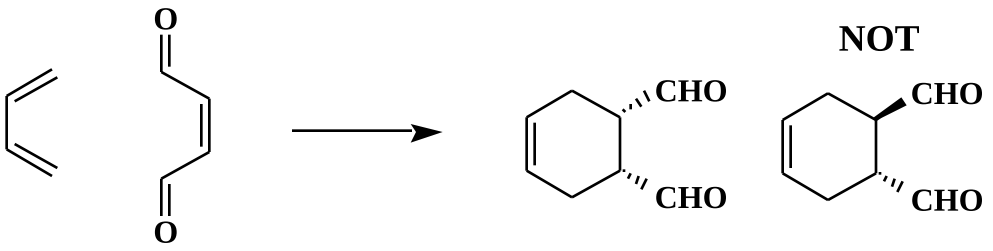
(2) The ene wants to be electron-poor (withdrawing groups)

Stereochemistry

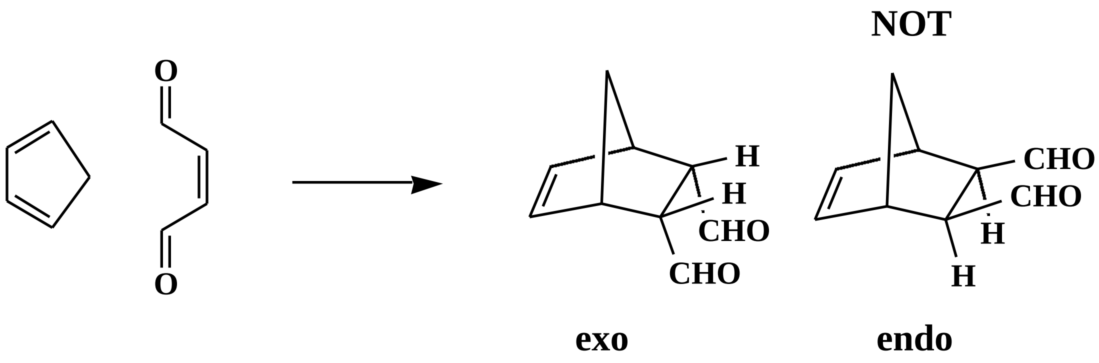
(1) The bonds to the “ene” are formed in a *cis* fashion!

(2) The large polar groups attached to the ene end up in the *exo* position (“under the diene”) and not in the *endo* position (away from the diene)

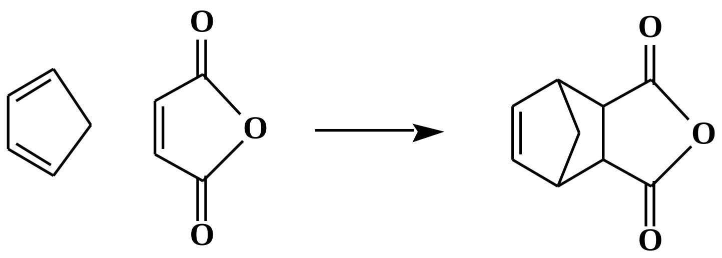
Example 1: Showing the *cis* addition.

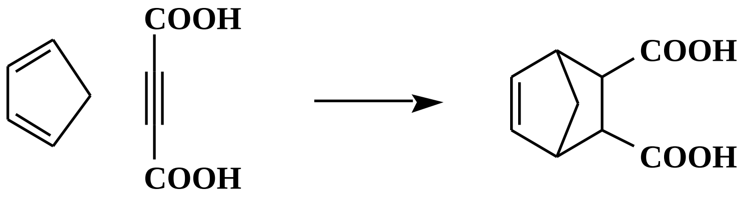


Example 2: Showing *exo* preference in case of cyclic dienes.



Example 3: Further typical examples.





More on the DA Reaction in Chapter 15 …