Chapter 8

Alkenes and Alkynes II: Addition Reactions

Created by
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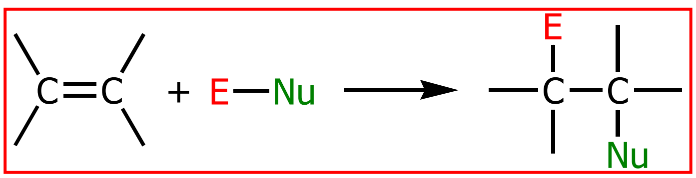
About The Authors

These PowerPoint Lecture Slides were created and prepared by Professor William Tam and his wife, Dr. Phillis Chang.

Professor William Tam received his B.Sc. at the University of Hong Kong in 1990 and his Ph.D. at the University of Toronto (Canada) in 1995. He was an NSERC postdoctoral fellow at the Imperial College (UK) and at Harvard University (USA). He joined the Department of Chemistry at the University of Guelph (Ontario, Canada) in 1998 and is currently a Full Professor and Associate Chair in the department. Professor Tam has received several awards in research and teaching, and according to *Essential Science Indicators*, he is currently ranked as the Top 1% most cited Chemists worldwide. He has published four books and over 80 scientific papers in top international journals such as *J. Am. Chem. Soc., Angew. Chem., Org. Lett.,* and *J. Org. Chem.*

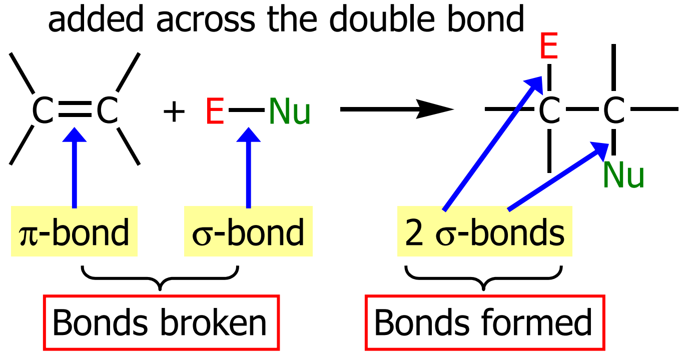
Dr. Phillis Chang received her B.Sc. at New York University (USA) in 1994, her M.Sc. and Ph.D. in 1997 and 2001 at the University of Guelph (Canada). She lives in Guelph with her husband, William, and their son, Matthew.

1. Addition Reactions of Alkenes

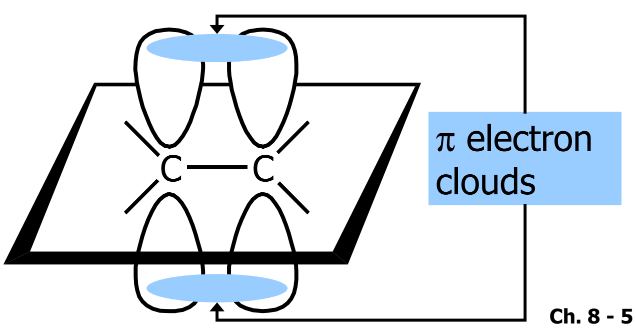


1A. How To Understand Additions to Alkenes

- This is an addition reaction: E–Nu added across the double bond

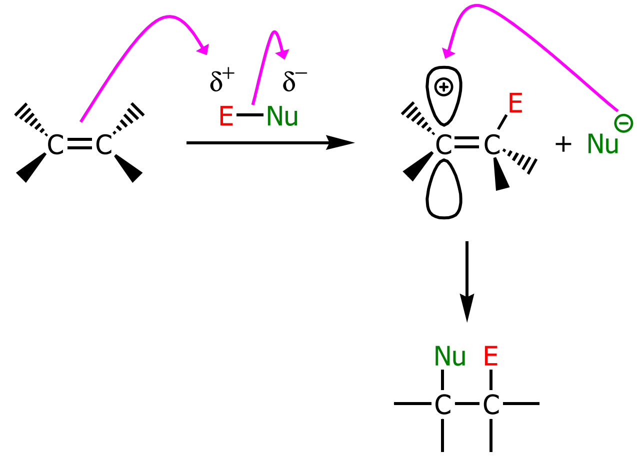


- Since p bonds are formed from the overlapping of π orbitals, π electron clouds are above and below the plane of the double bond



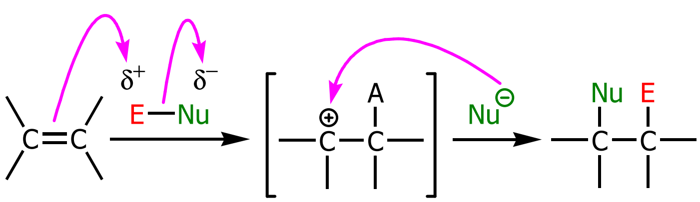
- Electrophilic
  - electron seeking
  - C=C and C≡C π bonds are particularly susceptible to electrophilic reagents (electrophiles)
- Common electrophile
  - H^+, X^+ (X = Cl, Br, I), Hg^{2+}, etc.

- In an electrophilic addition, the π electrons seek an electrophile, breaking the π bond, forming a σ bond and leaving a positive charge on the vacant π orbital on the adjacent carbon. Addition of B^- to form a σ bond provides an addition product

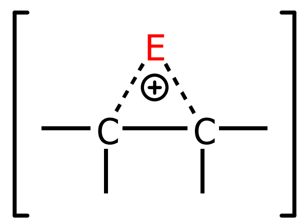


2. Electrophilic Addition of Hydrogen Halides to Alkenes: Mechanism and Markovnikov's Rule

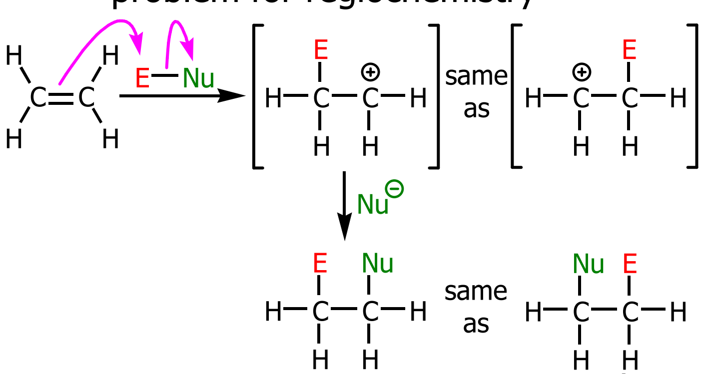
- Mechanism



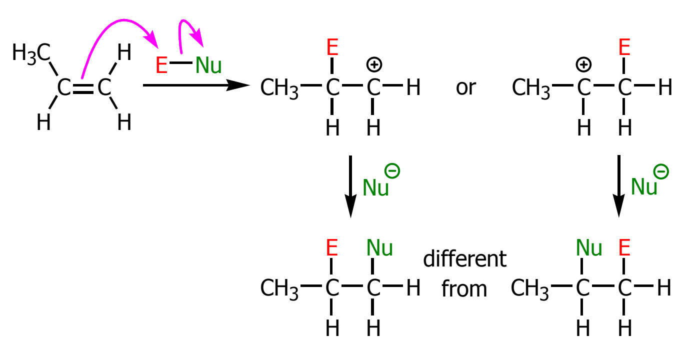
- Mechanism
  - Sometimes do not go through a "free carbocation", may go via



- Markovnikov's Rule
  - For symmetrical substrates, no problem for regiochemistry

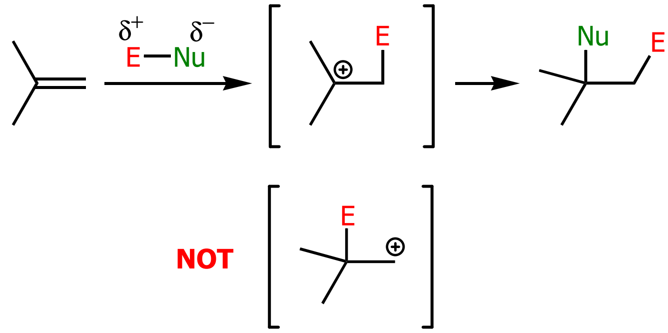


- Markovnikov's Rule
  - But for unsymmetrical substrates, two regioisomers are possible



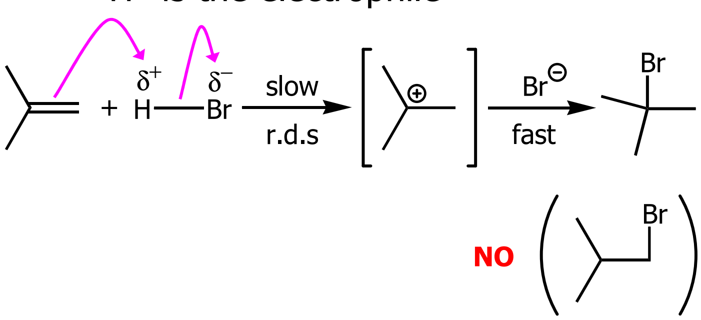
- Markovnikov's Rule
  - In the electrophilic addition of an unsymmetrical electrophile across a double bond of an alkene, the more highly substituted and more stabilized carbocation is formed as the intermediate in preference to the less highly substituted and less stable one

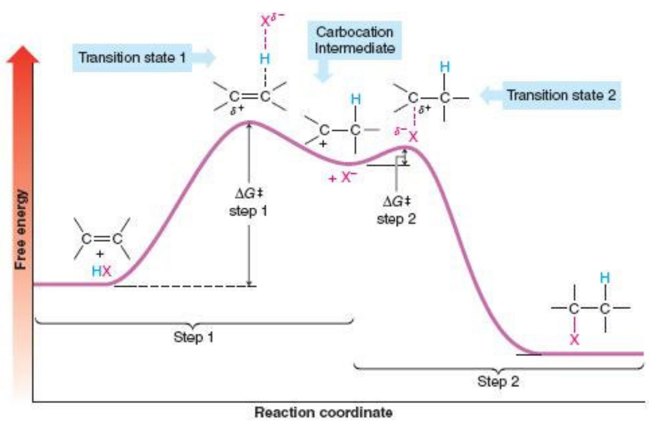
- Markovnikov's Rule
  - Thus



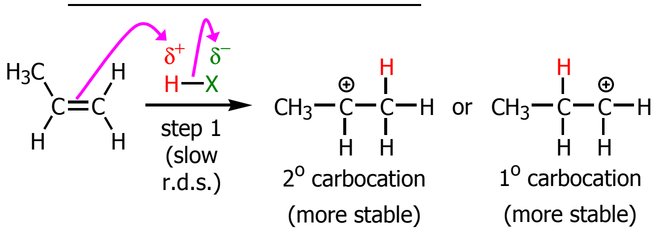
Note: carbocation stability ⇒ $3^o > 2^o > 1^o$

- Addition of Hydrogen Halides
  - Addition of HCl, HBr and HI across a C=C bond
  - H^+ is the electrophile

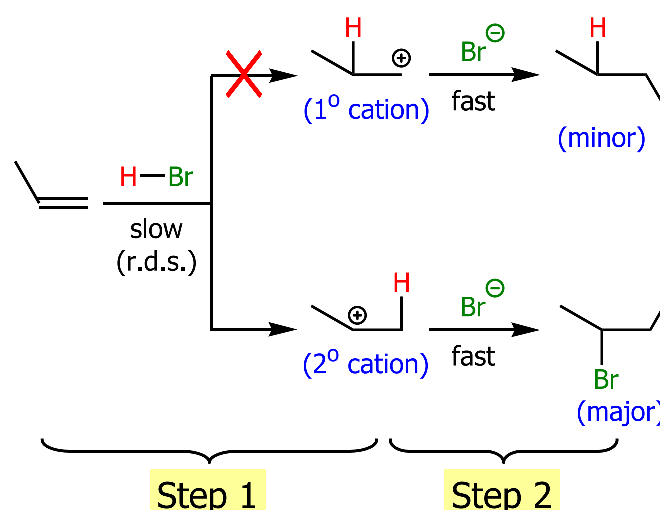


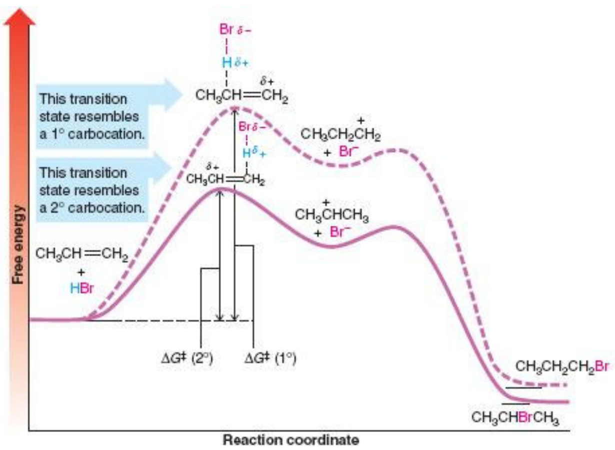


2A. Theoretical Explanation of Markovnikov's Rule

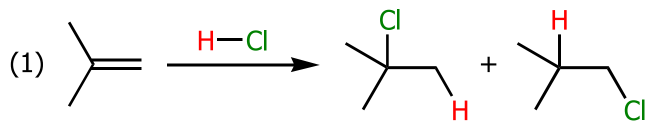


- One way to state Markovnikov's rule is to say that in the addition of HX to an alkene, the hydrogen atom adds to the carbon atom of the double bond that already has the greater number of hydrogen atoms





❖ Examples



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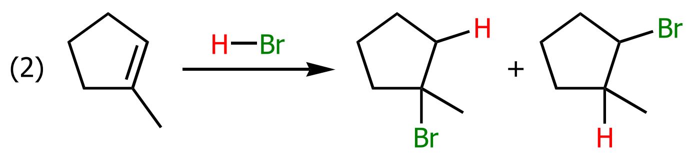
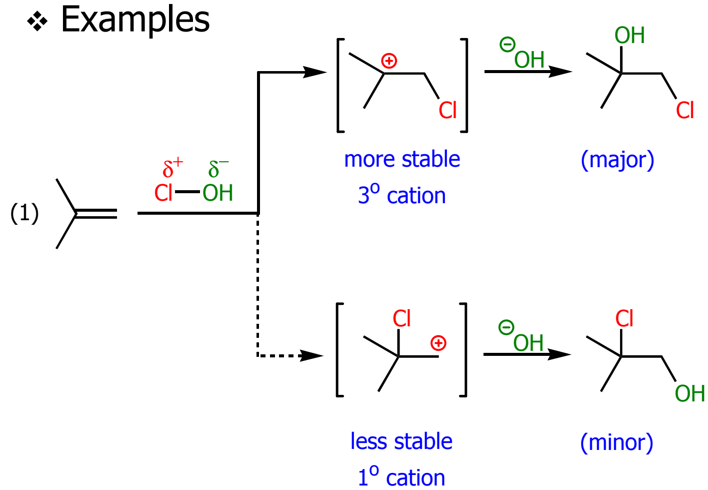


(98 : 2)

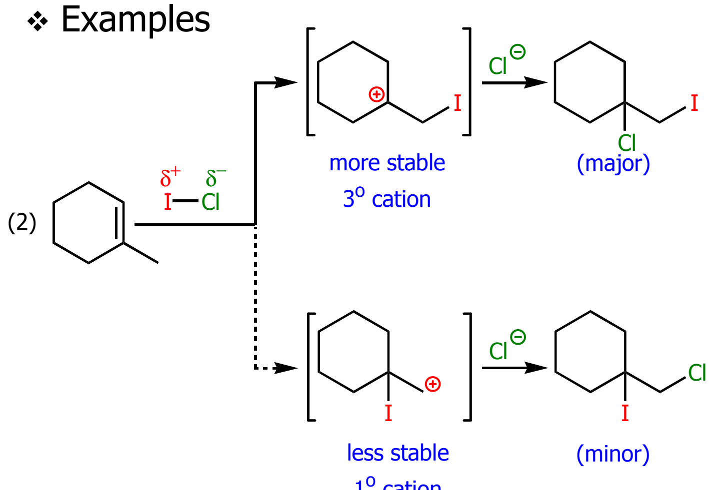
2B. Modern Statement of Markovnikov's Rule

❖ In the ionic addition of an unsymmetrical reagent to a double bond, the positive portion of the added reagent attaches itself to a carbon atom of the double bond so as to yield the more stable carbocation as an intermediate

❖ Examples

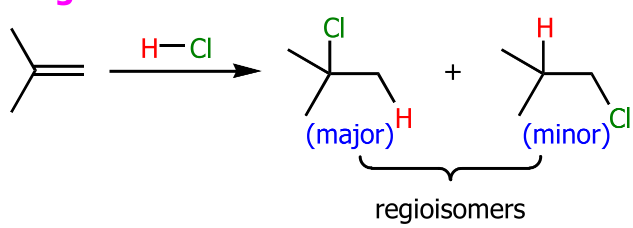


❖ Examples



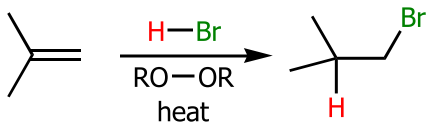
2C. Regioselective Reactions

❖ When a reaction that can potentially yield two or more constitutional isomers actually produces only one (or a predominance of one), the reaction is said to be **regioselective**



Regioselectivity: 95 : 5

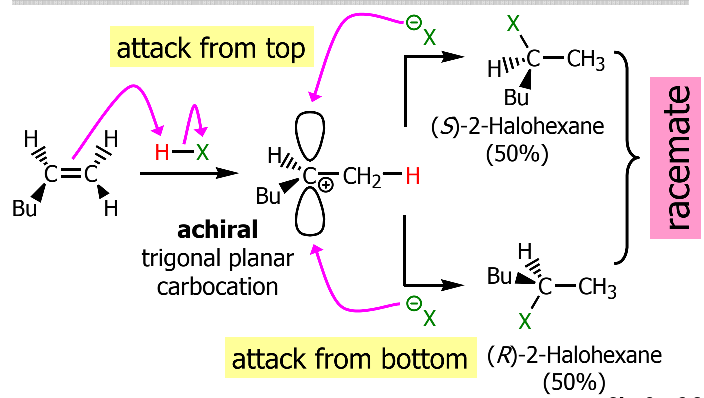
2D. An Exception to Markovnikov's Rule



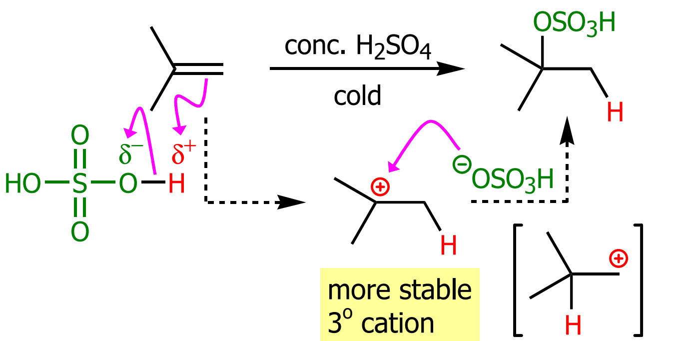
(anti-Markovnikov's product)

- Via a radical mechanism (see Chapter 10)
- This anti-Markovnikov addition does not take place with HI, HCl, and HF, even when peroxides are present

3. Stereochemistry of the Ionic Addition to an Alkene

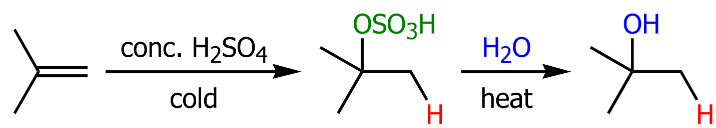


4. Addition of Sulfuric Acid to Alkenes



- Addition of H–OSO$_3$H across a C=C bond

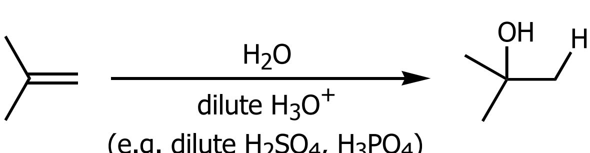
4A. Alcohols from Alkyl Hydrogen Sulfates



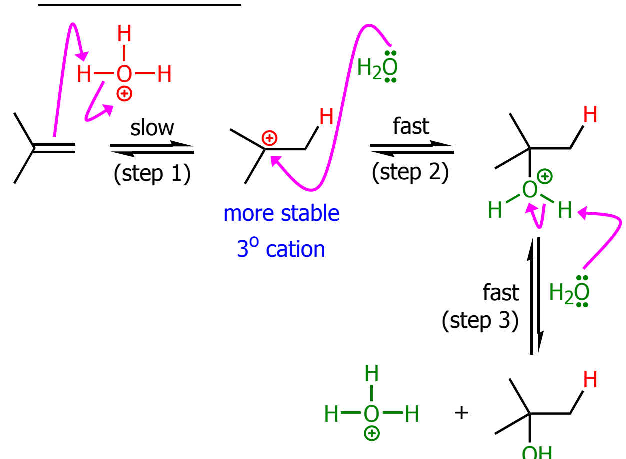
- The overall result of the addition of sulfuric acid to an alkene followed by hydrolysis is the Markovnikov addition of H– and –OH

5. Addition of Water to Alkenes: Acid-Catalyzed Hydration

- Overall process
  - Addition of H–OH across a C=C bond
  - H^+ is the electrophile
  - Follow Markovnikov's rule

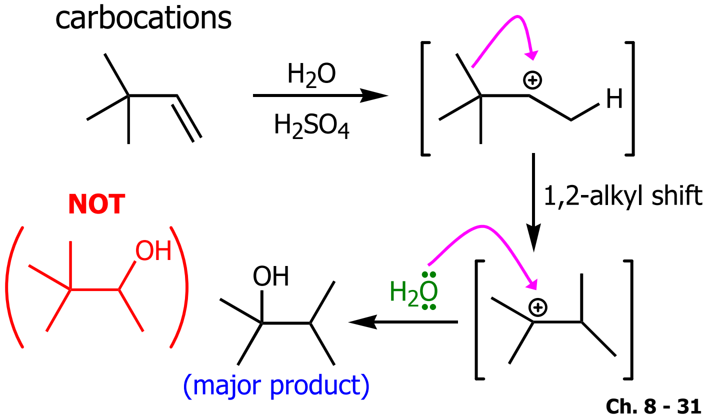


5A. Mechanism



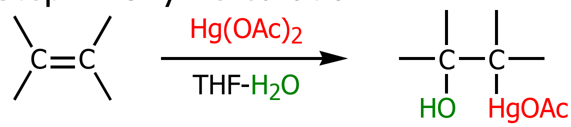
5B. Rearrangements

❖ Rearrangement can occur with certain carbocations

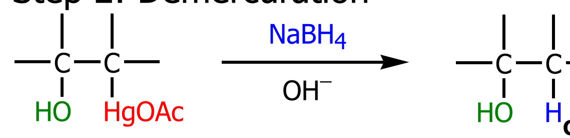


6. Alcohols from Alkenes through Oxymercuration–Demercuration: Markovnikov Addition

❖ Step 1: Oxymercuration

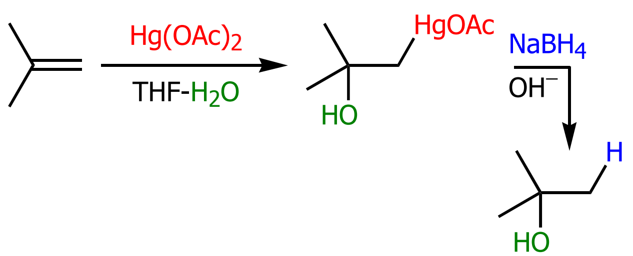


❖ Step 2: Demercuration



6A. Regioselectivity of Oxymercuration–Demercuration

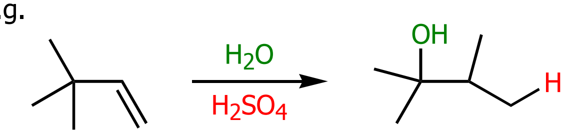
❖ Oxymercuration–demercuration is also highly regioselective and follows Markovnikov's rule

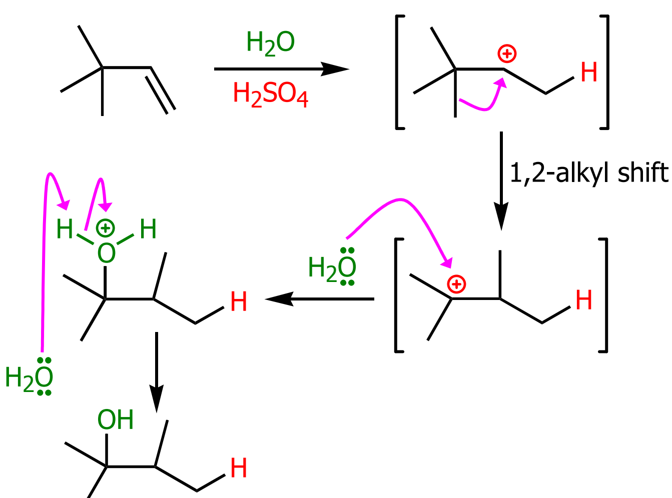


6B. Rearrangements Seldom Occur in Oxymercuration–Demercuration

❖ Recall: acid-catalyzed hydration of some alkenes leads to rearrangement products

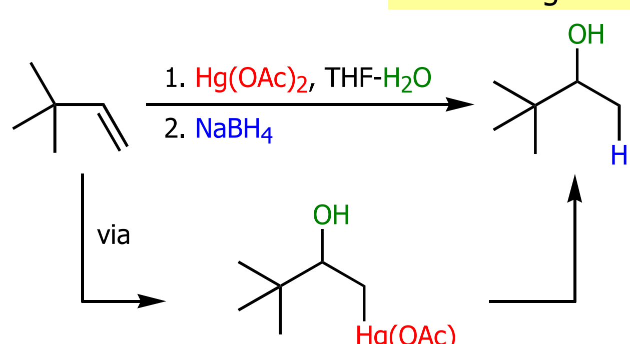
e.g.





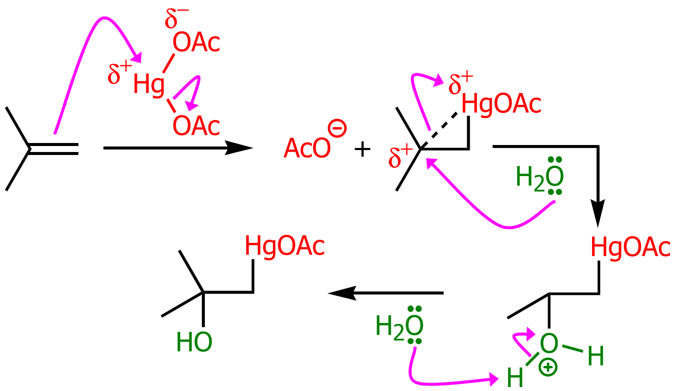
❖ Rearrangements of the carbon skeleton seldom occur in oxymercuration–demercuration

no rearrangement

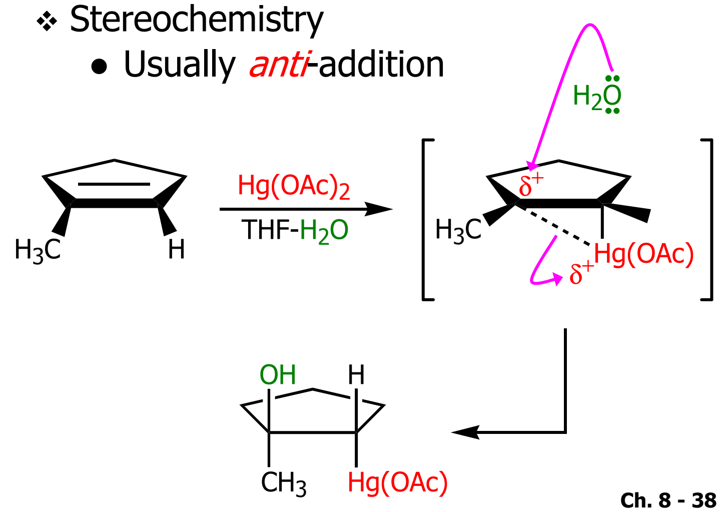


6C. Mechanism of Oxymercuration

- ❖ Does not undergo a "free carbocation"

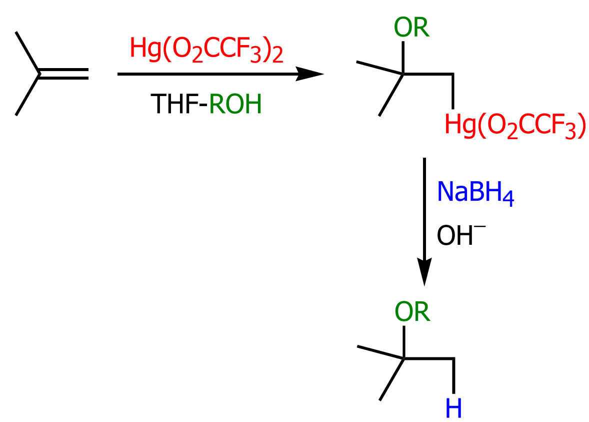


- ❖ Stereochemistry
  - Usually *anti*-addition

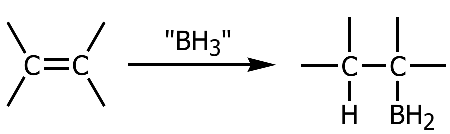


- ❖ Although attack by water on the bridged mercurinium ion leads to *anti* addition of the hydroxyl and mercury groups, the reaction that replaces mercury with hydrogen is not stereocontrolled (it likely involves radicals). This step scrambles the overall stereochemistry
- ❖ The net result of oxymercuration–demercuration is a mixture of *syn* and *anti* addition of –H and –OH to the alkene

- ❖ Solvomercuration-Demercuration

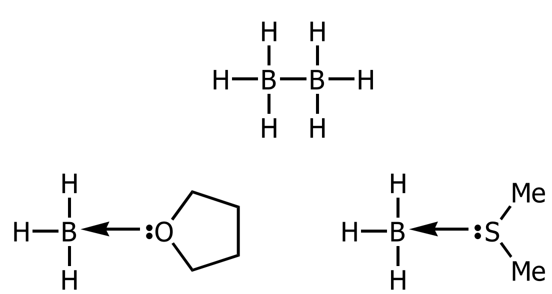


7. Alcohols from Alkenes through Hydroboration–Oxidation: Anti-Markovnikov Syn Hydration



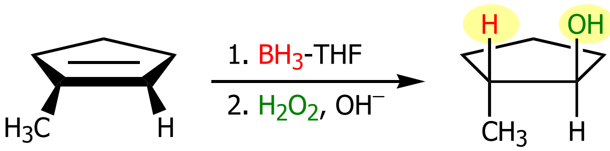
- ❖ Addition of H–BH_2 across a C=C bond

- ❖ BH_3 exists as dimer B_2H_6 or complex with coordinative solvent



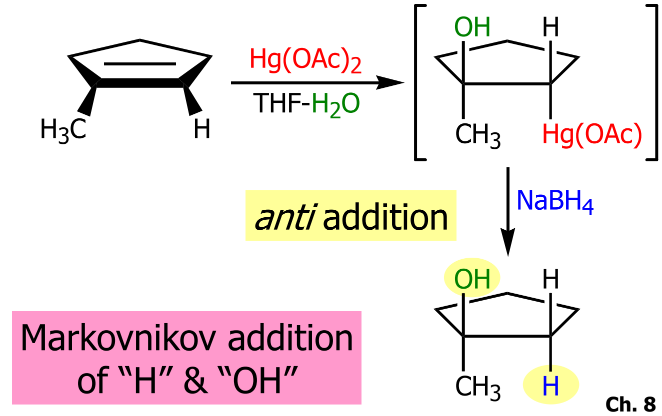
(BH_3-THF) (BH_3-DMS)

syn addition

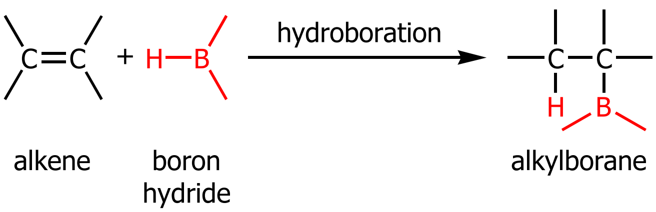


Anti-Markovnikov addition of “H” & “OH”

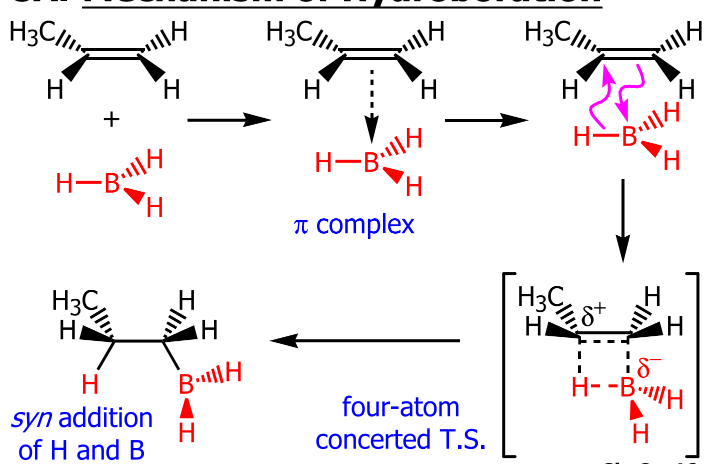
❖ Compare with oxymercuration-demercuration



8. Hydroboration: Synthesis of Alkylboranes

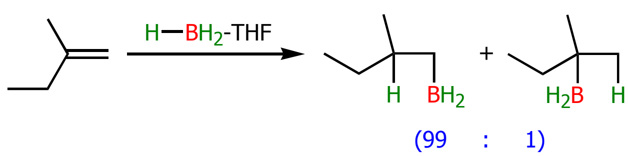


8A. Mechanism of Hydroboration



❖ Other examples

(1)



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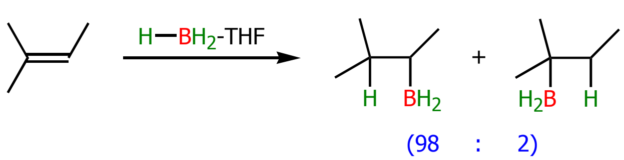
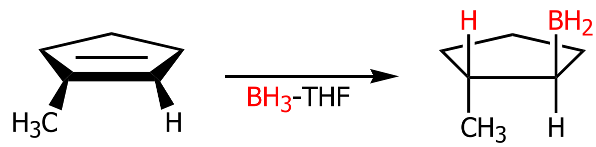
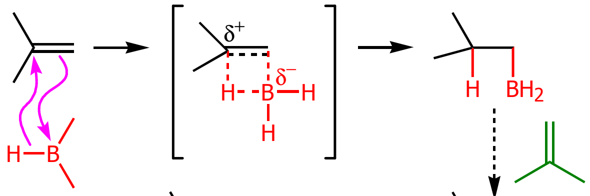


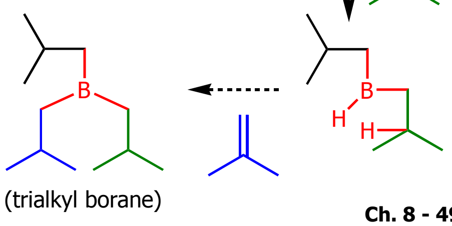
8B. Stereochemistry of Hydroboration

❖ Syn addition



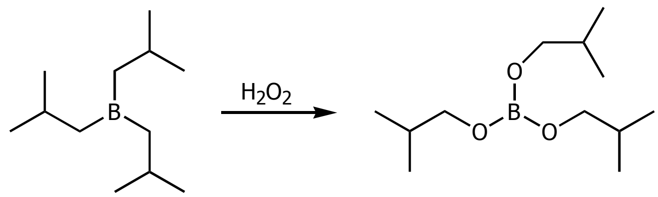
9. Oxidation and Hydrolysis of Alkylboranes



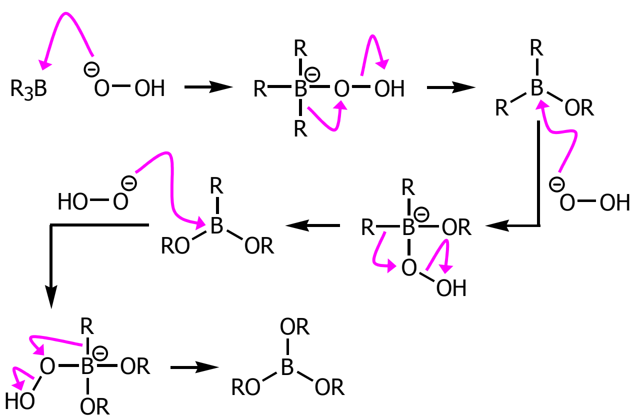


B always ends up on the least hindered carbon

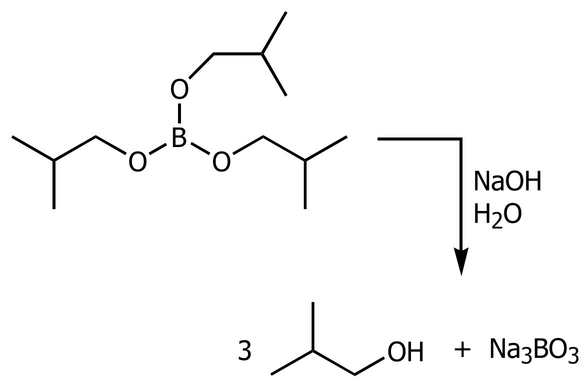
❖ Oxidation



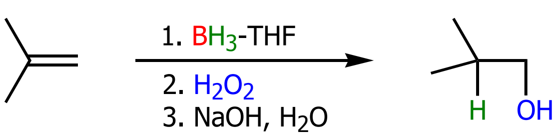
- Via



❖ Hydrolysis



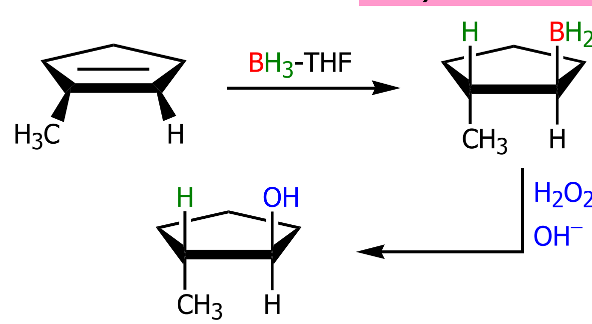
❖ Overall synthetic process of hydroboration-oxidation-hydrolysis



- Overall: anti-Markovnikov addition of H–OH across a C=C bond
- Opposite regioisomers as oxymercuration-demercuration

❖ Example

anti-Markovnikov *syn* addition



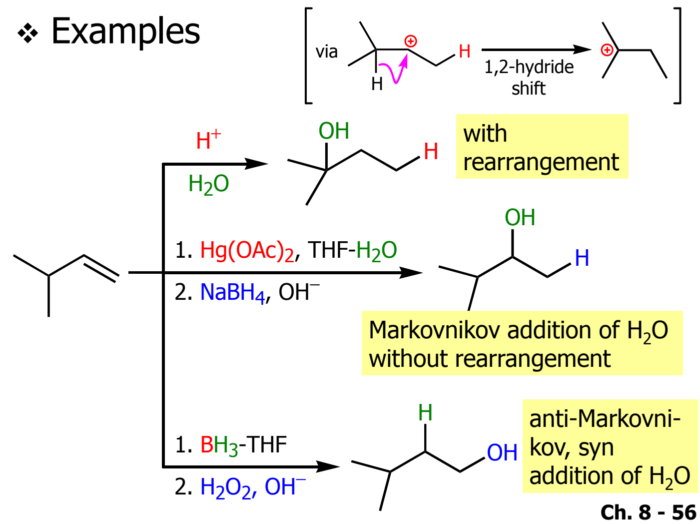
This oxidation step occurs with ***retention of configuration***

10. Summary of Alkene Hydration Methods

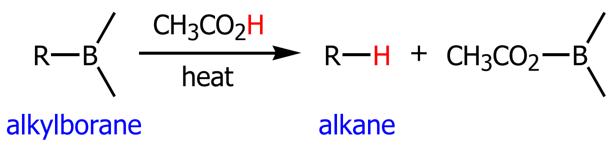
Summary of Methods for Converting Alkene to Alcohol

Reaction	*Regiochemistry*	*Stereochemistry*	*Occurrence of Rearrangements*
Acid-catalyzed hydration	Markovnikov addition	Not controlled	Frequent
Oxymercuration-demercuration	Markovnikov addition	Not controlled	Seldom
Hydroboration-oxidation	Anti-Markovnikov addition	Stereospecific: *syn* addition of H – and –OH	Seldom

❖ Examples

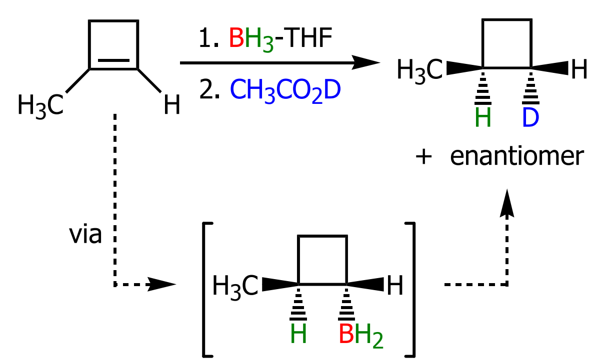


11. Protonolysis of Alkylboranes



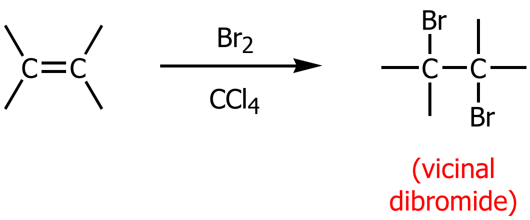
- ❖ Protonolysis of an alkylborane takes place with retention of configuration; hydrogen replaces boron **where it stands** in the alkylborane
- ❖ Overall stereochemistry of hydroboration–protonolysis: **syn**

❖ e.g.

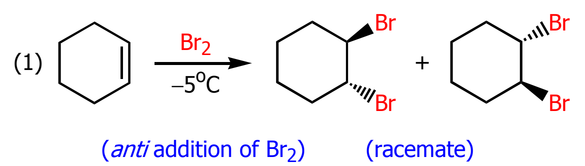


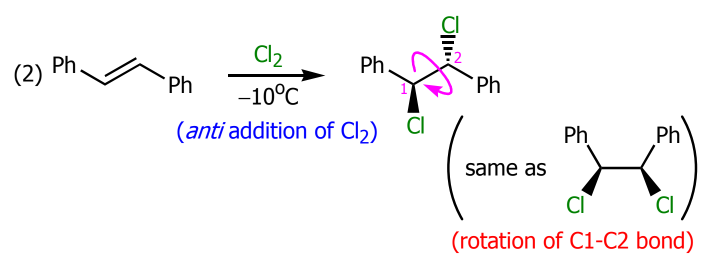
12. Electrophilic Addition of Bromine and Chlorine to Alkenes

- ❖ Addition of X–X (X = Cl, Br) across a C=C bond

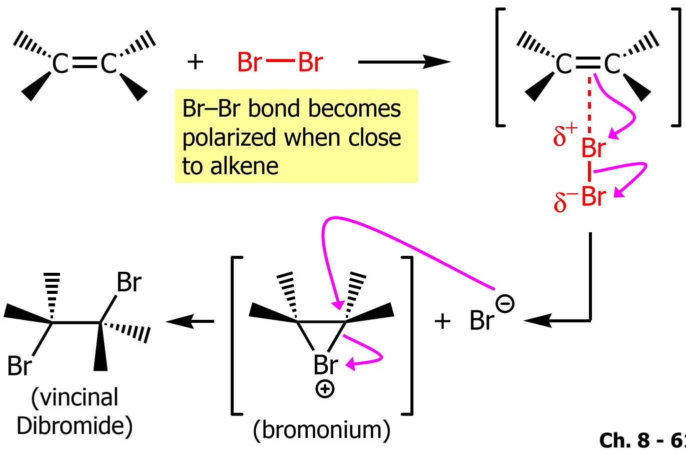


❖ Examples



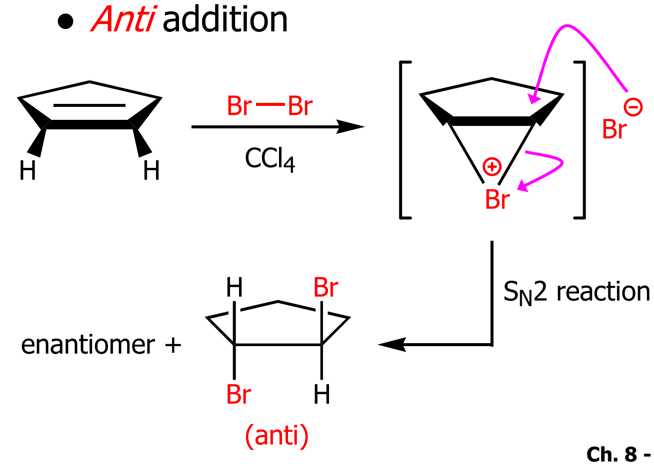


12A. Mechanism of Halogen Addition



❖ Stereochemistry

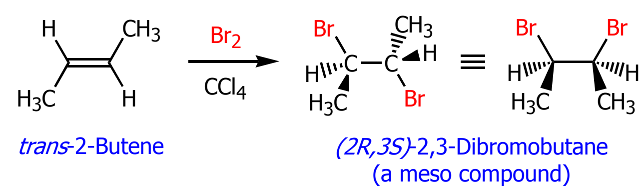
- *Anti* addition



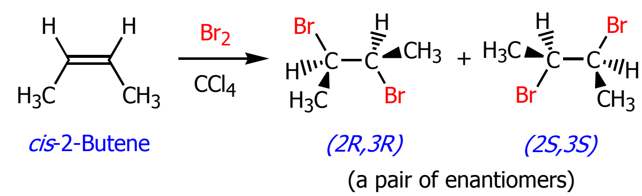
13. Stereospecific Reactions

❖ A reaction is stereospecific when a particular stereoisomeric form of the starting material reacts by a mechanism that gives a specific stereoisomeric form of the product

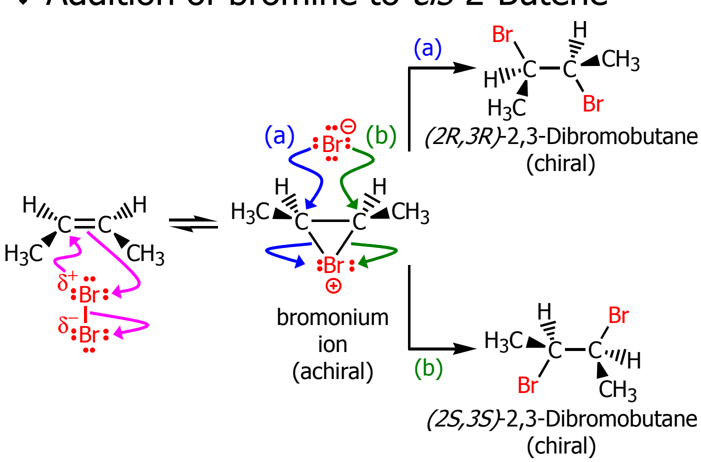
- Reaction 1



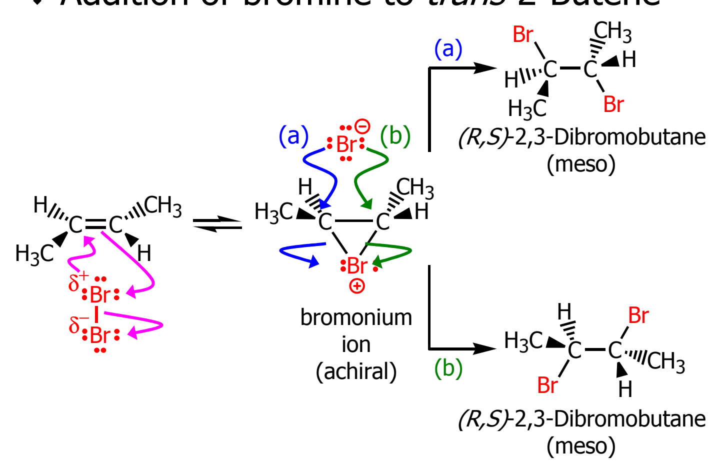
- Reaction 2



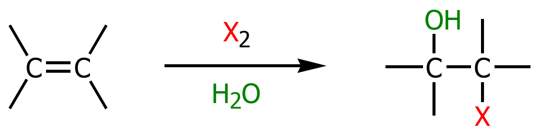
❖ Addition of bromine to *cis*-2-Butene



❖ Addition of bromine to *trans*-2-Butene

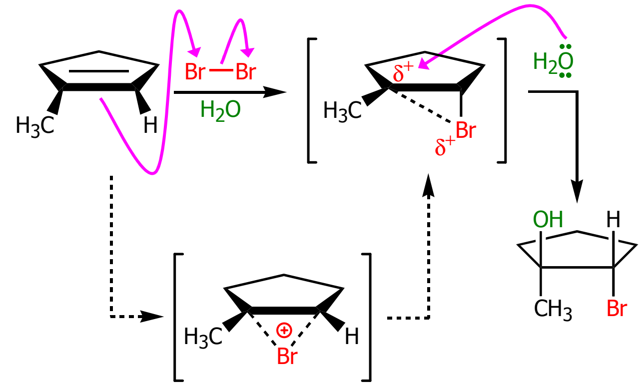


14. Halohydrin Formation



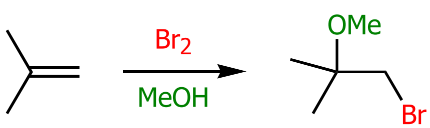
- Addition of –OH and –X (X = Cl, Br) across a C=C bond
- X^+ is the electrophile
- Follow Markovnikov's rule

- Mechanism



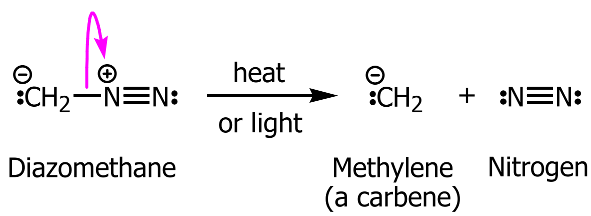
- Other variation
  - If H_2O is replaced by ROH, RÖH will be the nucleophile

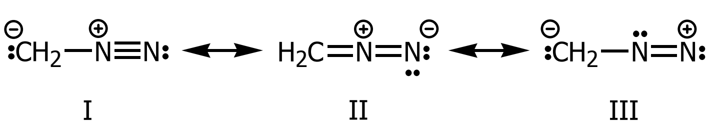
e.g.

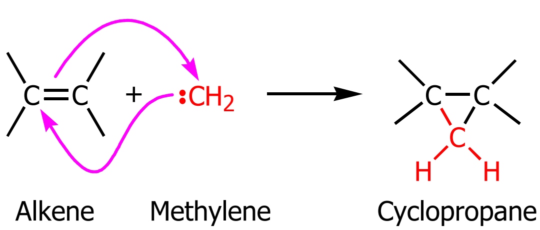


15. Divalent Carbon Compounds: Carbenes

15A. Structure and Reactions of Methylene

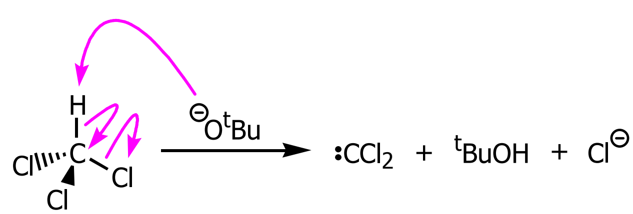




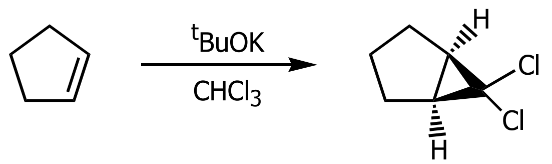


15B. Reactions of Other Carbenes: Dihalocarbenes

- $:CX_2$ (e.g. $:CCl_2$)
- Generation by α-elimination of chloroform

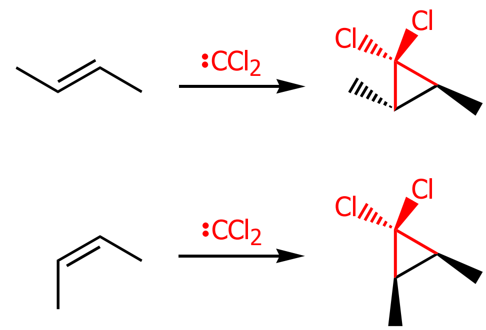


- Usually a *syn* (*cis*) addition across a C=C bond

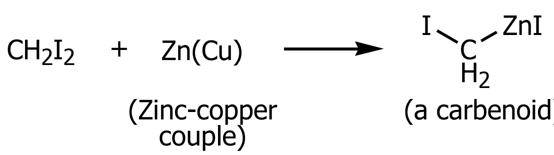


(a cyclopropane)

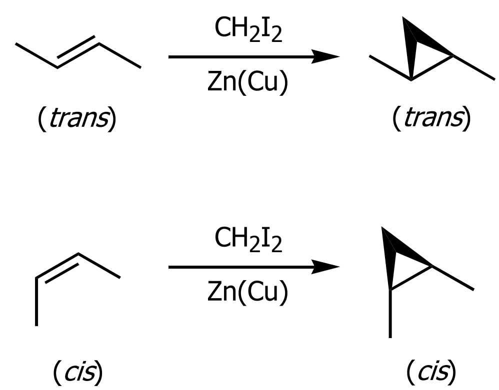
- Stereospecific reactions



15C. Carbenoids: The Simmons-Smith Cyclopropane Synthesis

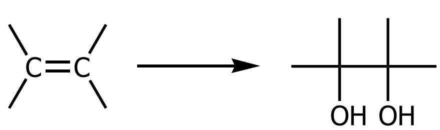


- A stereospecific *syn* (*cis*) addition across a C=C bond



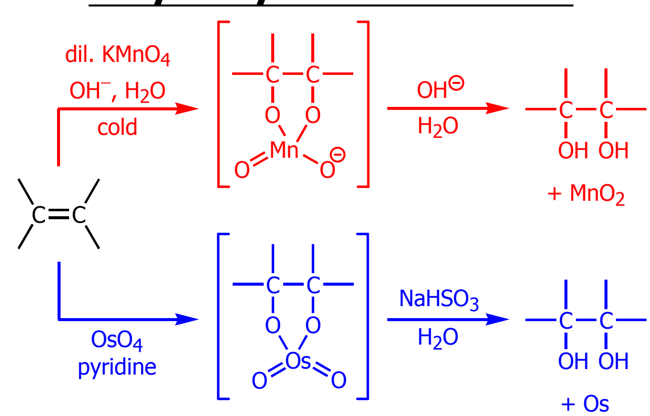
16. Oxidation of Alkenes: Syn 1,2-Dihydroxylation

- Overall: addition of 2 OH groups across a C=C bond

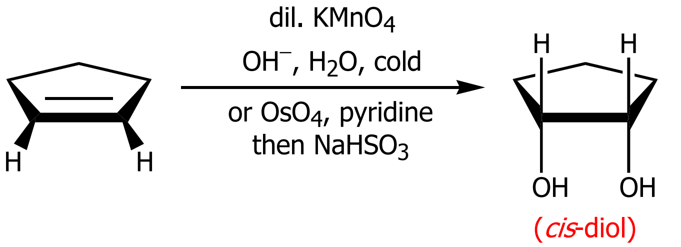


- Reagents: dilute $KMnO_4$ / $OH^{\ominus}$ / H_2O / cold or OsO_4, pyridine then $NaHSO_3$, H_2O

16A. Mechanism for Syn Dihydroxylation of Alkenes

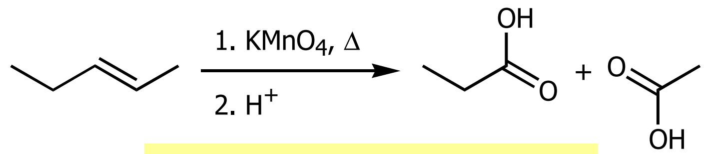


❖ Both reagents give *syn* dihydroxylation



❖ Comparison of the two reagents

- $KMnO_4$: usually lower yield and possibly side products due to over-oxidation

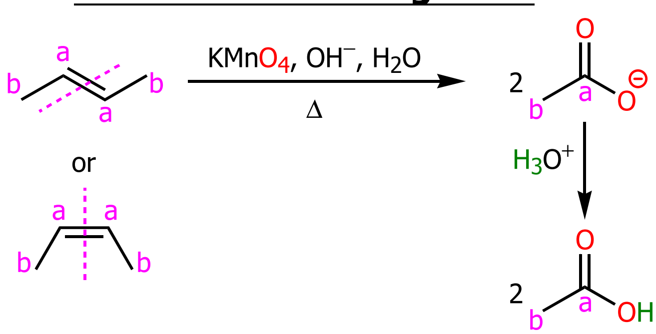


(oxidative cleavage of C=C)

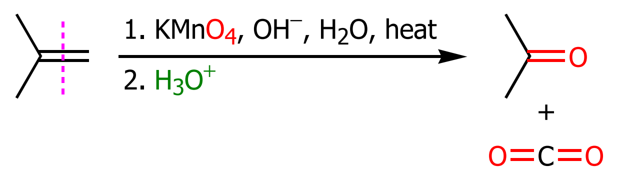
- OsO_4: usually much higher yield but OsO_4 is extremely toxic

17. Oxidative Cleavage of Alkenes

17A. Cleavage with Hot Basic Potassium Permanganate



❖ Other examples

(1)


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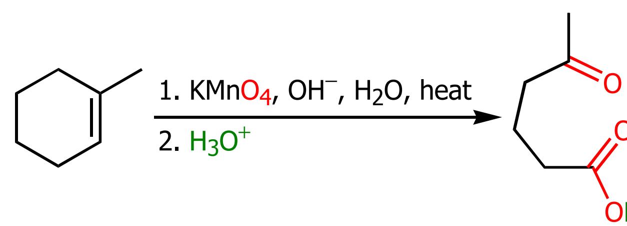
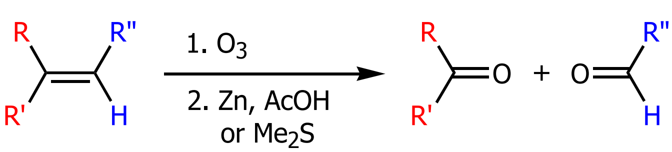
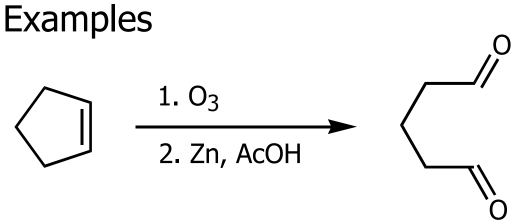
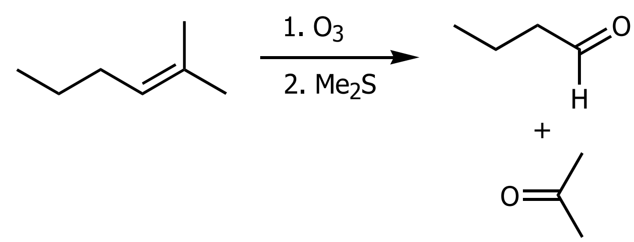


17B. Cleavage with Ozone

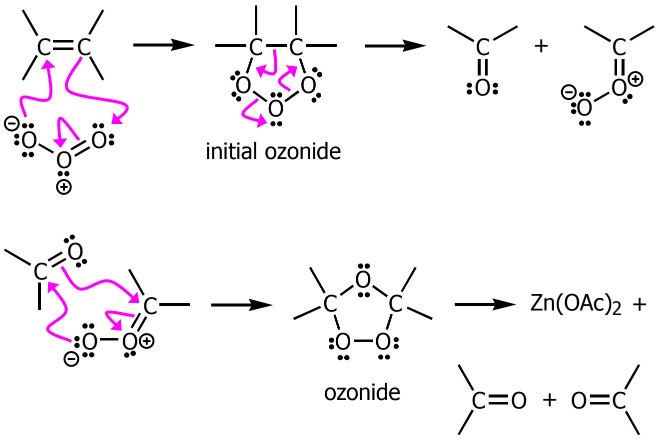


❖ Examples

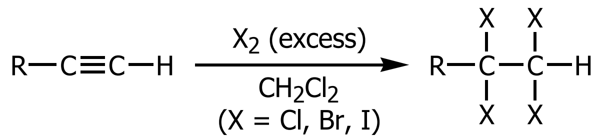
(1)


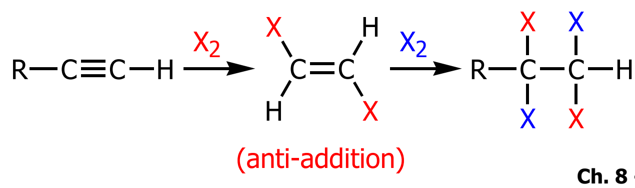
(2)


❖ Mechanism

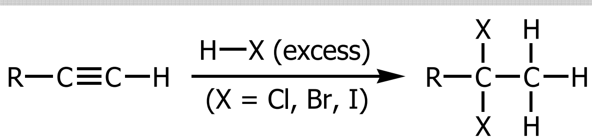


18. Electrophilic Addition of Bromine & Chlorine to Alkynes



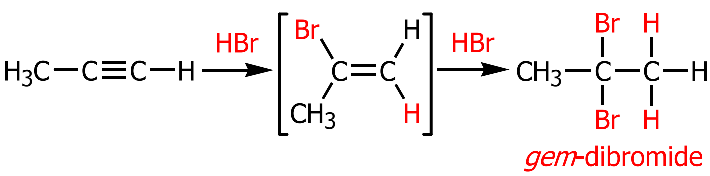


19. Addition of Hydrogen Halides to Alkynes

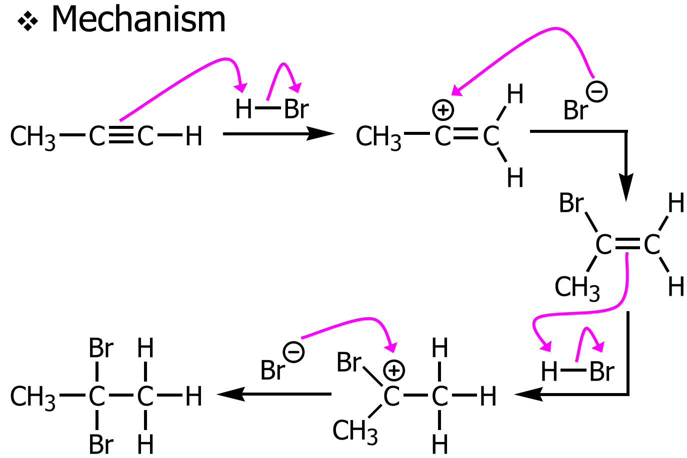


❖ Regioselectivity

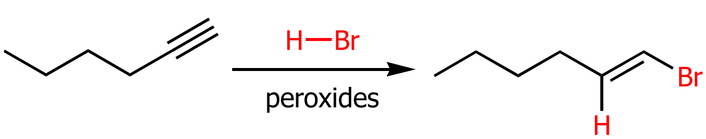
- Follow Markovnikov's rule



❖ Mechanism



❖ Anti-Markovnikov addition of hydrogen bromide to alkynes occurs when peroxides are present in the reaction mixture



(*E*) and (*Z*)

(74%)

20. Oxidative Cleavage of Alkynes

$$R{-}C{\equiv}C{-}R' \xrightarrow[\text{2. HOAc}]{\text{1. } O_3} RCO_2H + R'CO_2H$$

OR

$$R{-}C{\equiv}C{-}R' \xrightarrow[\text{2. } H_3O^+]{\text{1. } KMnO_4,\ OH^-} RCO_2H + R'CO_2H$$

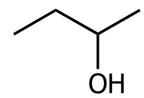
❖ Example

$$Ph{-}C{\equiv}C{-}CH_3 \xrightarrow[\text{2. AcOH}]{\text{1. } O_3} PhCO_2H + CH_3CO_2H$$

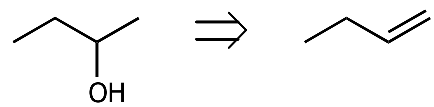
21. How to Plan a Synthesis: Some Approaches & Examples

- In planning a synthesis we often have to consider four interrelated aspects:
  1. Construction of the carbon skeleton
  2. Functional group interconversions
  3. Control of regiochemistry
  4. Control of stereochemistry

21A. Retrosynthetic Analysis

- How to synthesize  ?

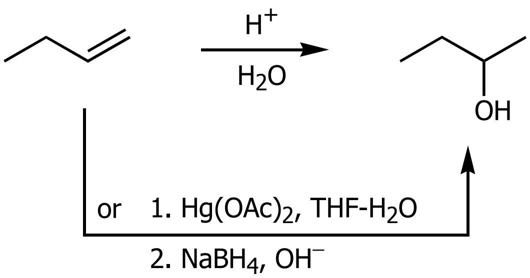
- Retrosynthetic analysis

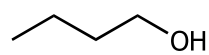


(target molecule) (precursor)

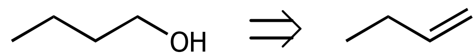
- Synthesis

Markovnikov addition of H_2O



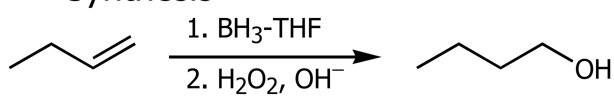
- How to synthesize  ?

- Retrosynthetic analysis



(target molecule) (precursor)

- Synthesis

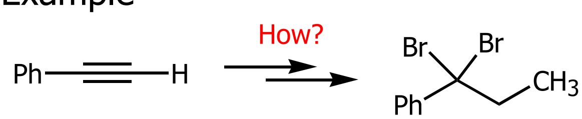


anti-Markovnikov addition of H_2O

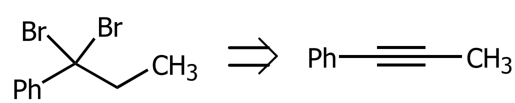
21B. Disconnections, Synthons, and Synthetic Equivalents

- One approach to retrosynthetic analysis is to consider a retrosynthetic step as a "disconnection" of one of the bonds
- In general, we call the fragments of a hypothetical retrosynthetic disconnection **Synthons**

- Example

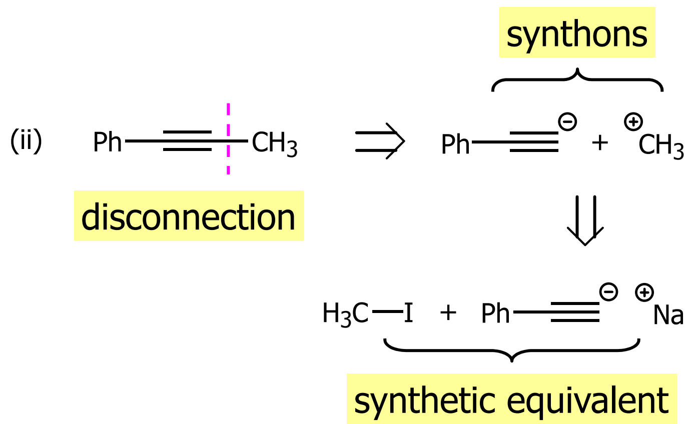


- Retrosynthetic analysis

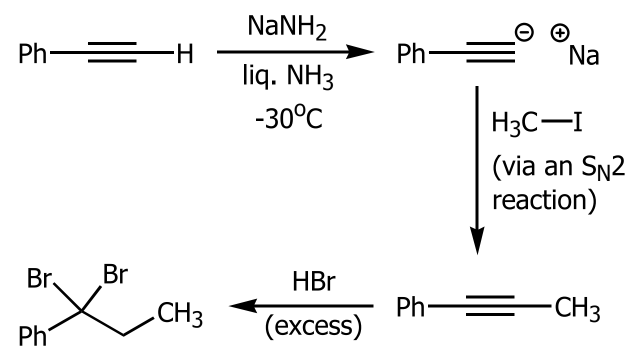
(i) 

(gem-dibromide came from addition of HBr across a C≡C bond)

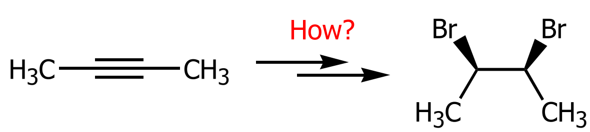
- Retrosynthetic analysis



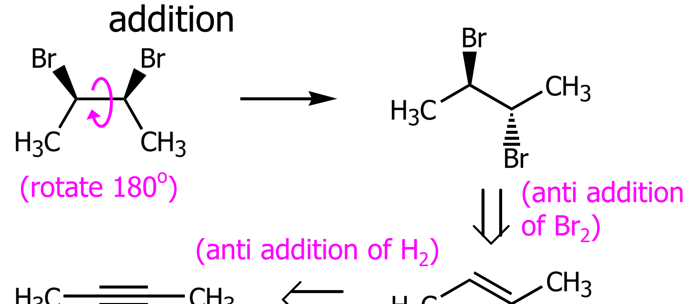
- Synthesis



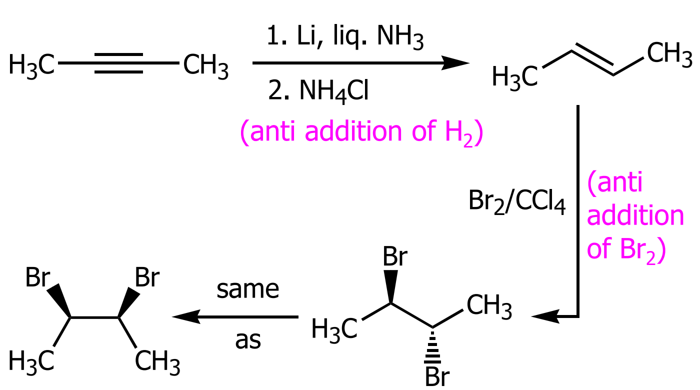
21C. Stereochemical Considerations



❖ Retrosynthetic analysis
- The precursor of a vicinal dibromide is usually an alkene
- Bromination of alkenes are anti addition



- Synthesis



🔔 END OF CHAPTER 8 🔔