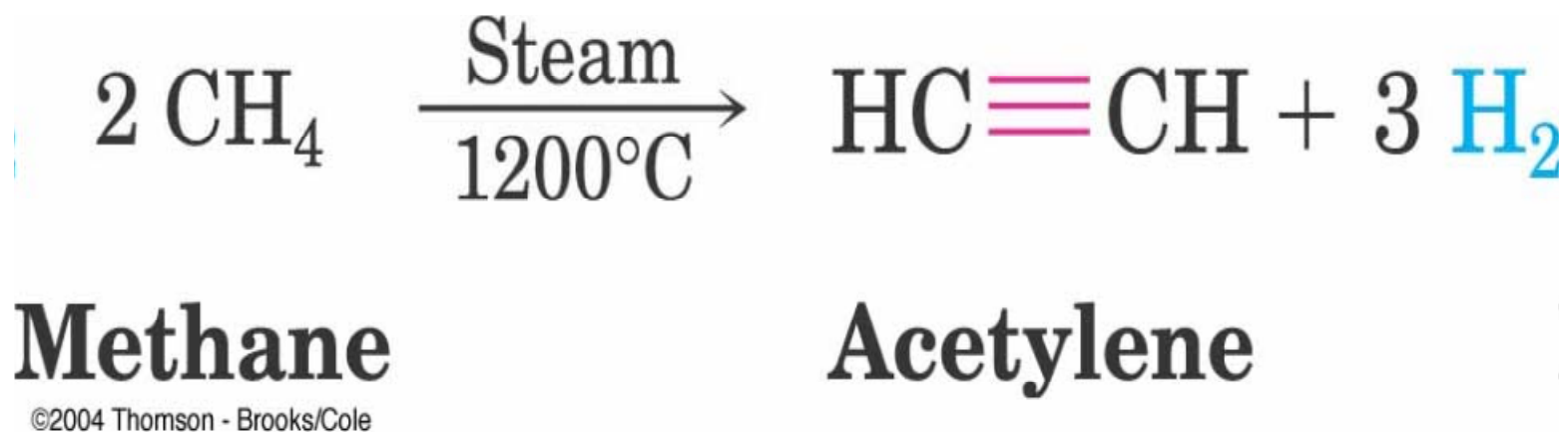


# Alkynes: An Introduction to Organic Synthesis

Based on  
McMurry's *Organic Chemistry*, Chapter 8

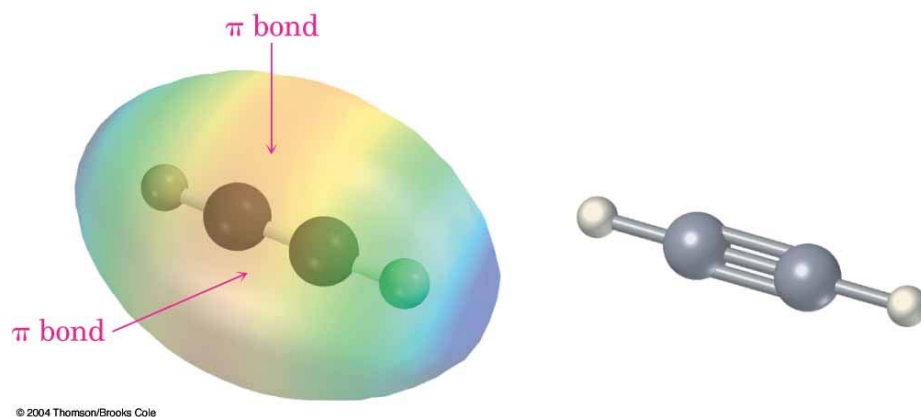
# Alkynes

- Hydrocarbons that contain carbon-carbon triple bonds
- Acetylene, the simplest alkyne is produced industrially from methane and steam at high temperature
- Our study of alkynes provides an introduction to organic synthesis, the preparation of organic molecules from simpler organic molecules



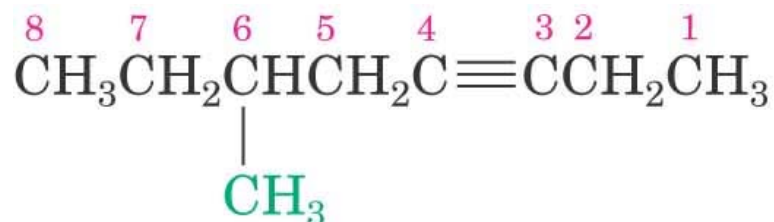
## 8.1 Electronic Structure of Alkynes

- Carbon-carbon triple bond results from  $sp$  orbital on each C forming a sigma bond and unhybridized  $p_x$  and  $p_y$  orbitals forming a  $\pi$  bond each.
- The remaining  $sp$  orbitals form bonds to other atoms at  $180^\circ$  to C-C triple bond.
- The bond is shorter and stronger than single or double
- Breaking a  $\pi$  bond in acetylene (HCCH) requires 318 kJ/mole (in ethylene it is 268 kJ/mole)



## 8.2 Naming Alkynes

- General hydrocarbon rules apply with “-yne” as a suffix indicating an alkyne
- Numbering of chain with triple bond is set so that the smallest number possible include the triple bond

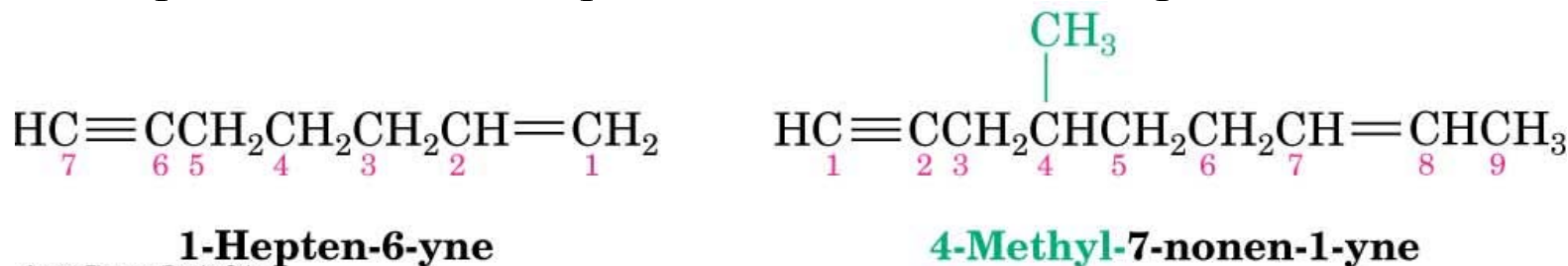


Begin numbering at the end nearer the triple bond.

**6-Methyl-3-optyne**

# Diyines, Enynes, and Triynes

- A compound with two triple bonds is a diyine
- An enyne has a double bond and triple bond
- A triyne has three triple bonds
- Number from chain that ends nearest a double or triple bond – double bonds is preferred if both are present in the same relative position



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Alkynes as substituents are called “alkynyl”



**Butyl**  
(an alkyl group)

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**1-Butenyl**  
(a vinylic group)

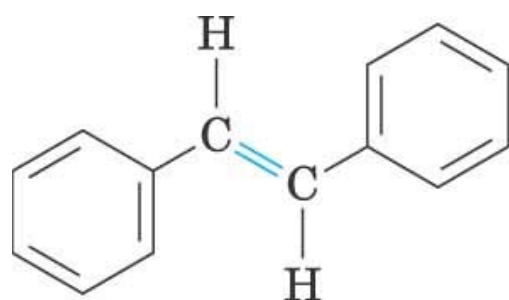


**1-Butynyl**  
(an alkynyl group)

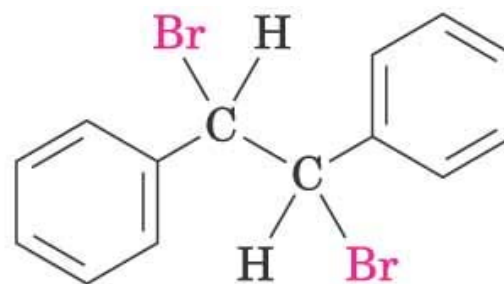
## 8.3 Preparation of Alkynes: Elimination Reactions of Dihalides

- Treatment of a 1,2 dihaloalkane with KOH or NaOH produces a two-fold elimination of HX (elimination of HX twice)
- Vicinal dihalides (2 halogens on two adjacent carbons) are available from addition of bromine or chlorine to an alkene

Elimination of HX from Vinyl halides provides another method for preparing alkynes



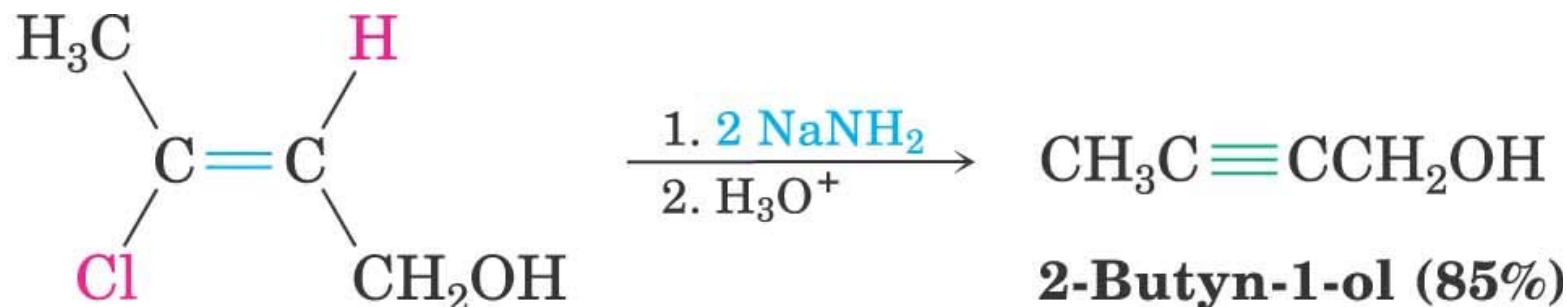
**1,2-Diphenylethylene  
(Stilbene)**



**1,2-Dibromo-1,2-diphenylethane  
(a vicinal dibromide)**



**Diphenylacetylene (85%)**



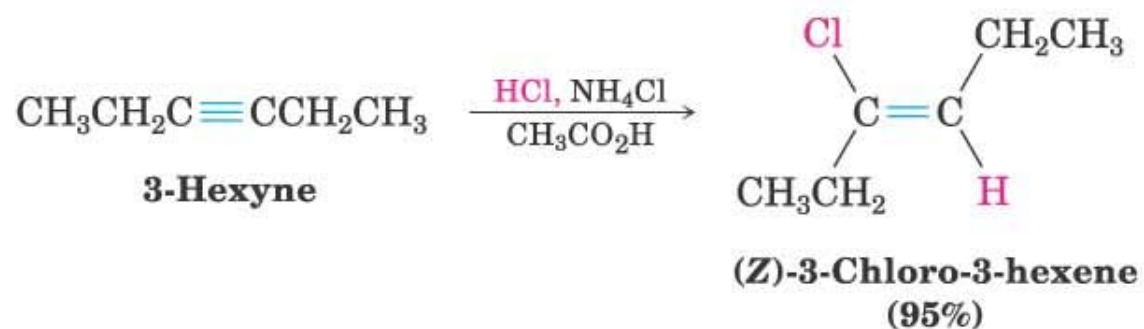
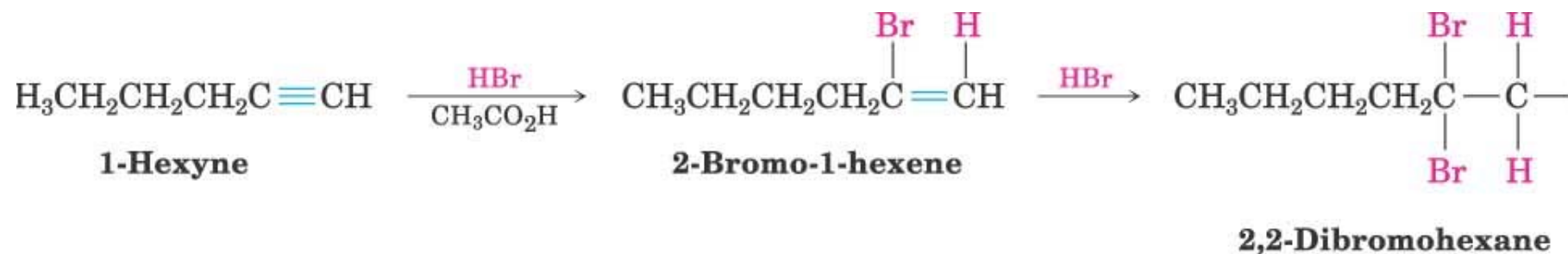
**3-Chloro-2-buten-1-ol**  
(a vinylic chloride)

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## 8.4 Reactions of Alkynes: Addition of HX and X<sub>2</sub>

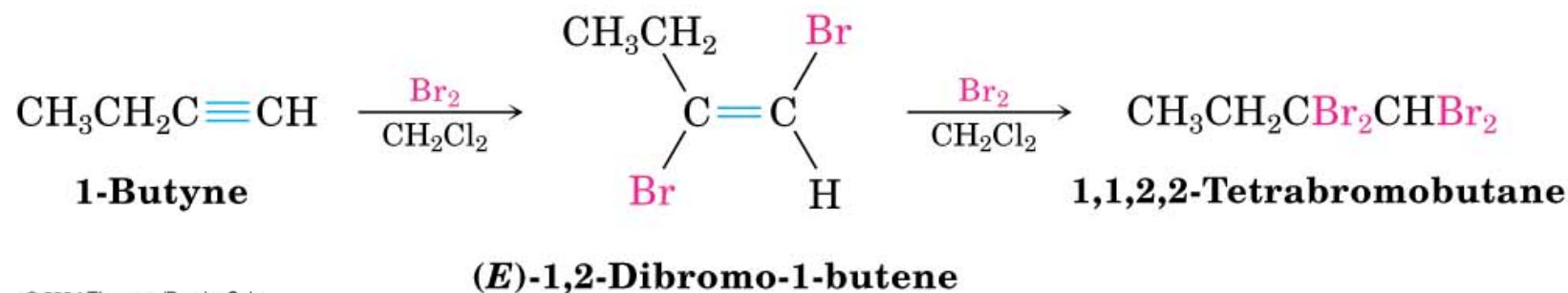
- Addition reactions of alkynes are similar to those of alkenes
- Intermediate alkene reacts further with excess reagent
- Regiospecificity according to **Markovnikov**





# Addition of Bromine and Chlorine

- Initial addition gives trans intermediate (trans addition mechanism, bromonium ion intermediate)
- Product with excess reagent is tetrahalide



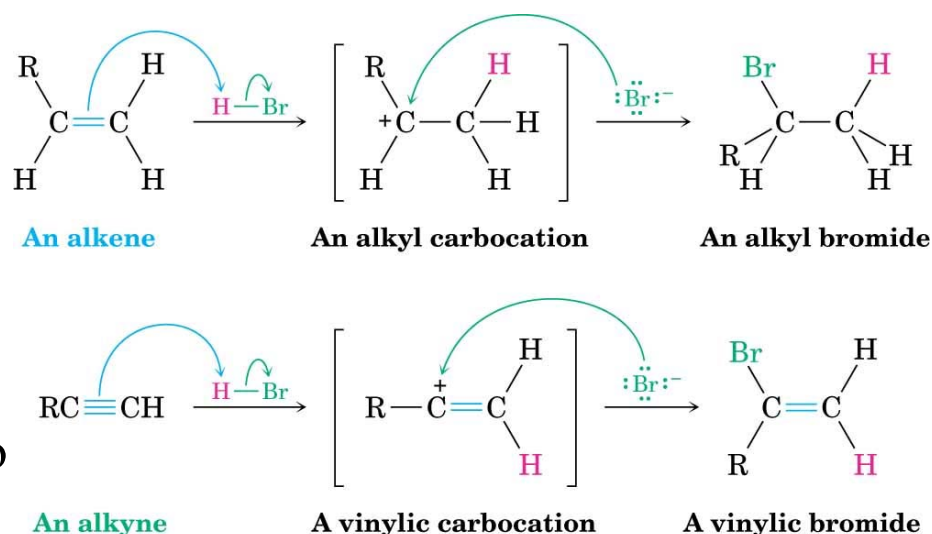
# Addition of HX to Alkynes Involves Vinylic Carbocations

- Addition of H-X to alkyne should produce a vinylic carbocation intermediate

- Secondary vinyl carbocations form less readily than primary alkyl carbocations

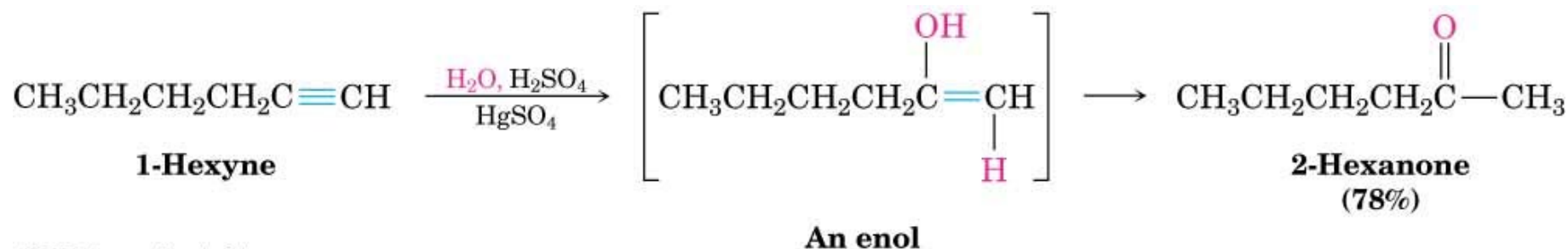
- Primary vinyl carbocations probably do not form at all

- Nonetheless, H-Br can add to an alkyne to give a vinyl bromide via a secondary vinylic carbocation.



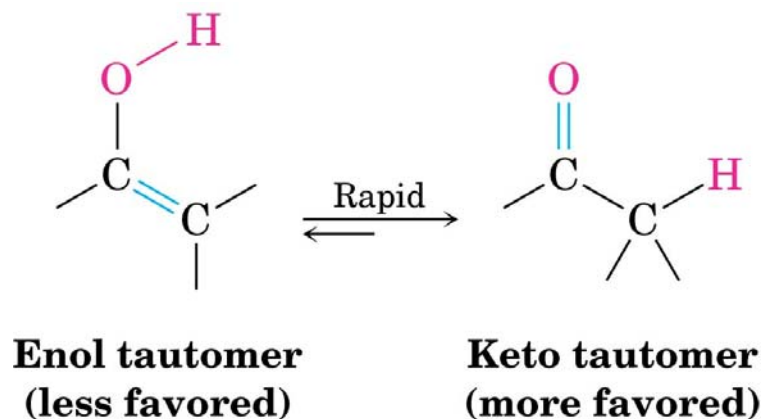
## 8.5 Hydration of Alkynes

- Addition of H-OH as in alkenes (Markovnikov or anti-Markovnikov product depending on methodology and reaction conditions)
- Mercury (II) catalyzes Markovnikov oriented addition
- Alkynes do not react with aqueous protic acids
- Mercuric ion (as the sulfate) is a Lewis acid catalyst that promotes addition of water in Markovnikov orientation
- The immediate product is a vinylic alcohol, or **enol**, which spontaneously rearranges itself to a ketone



# Keto-enol Tautomerism

- Isomeric compounds that can rapidly interconvert by the movement of a proton are called **tautomers** and the phenomenon is called tautomerism
- Enols rearrange to the isomeric ketone by the rapid transfer of a proton from the hydroxyl to the alkene carbon
- The keto form is usually so stable compared to the enol that only the keto form can be observed



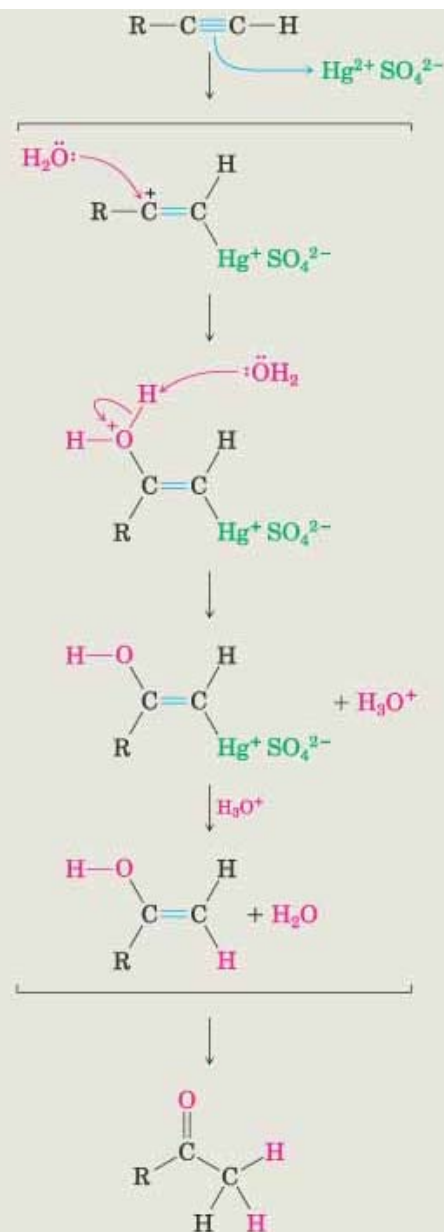
The alkyne uses a pair of electrons to attack the electrophilic mercury(II) ion, yielding a mercury-containing vinylic carbocation intermediate.

Nucleophilic attack of water on the carbocation forms a C-O bond and yields a protonated mercury-containing enol.

Abstraction of  $\text{H}^+$  from the protonated enol by water gives an organomercury compound.

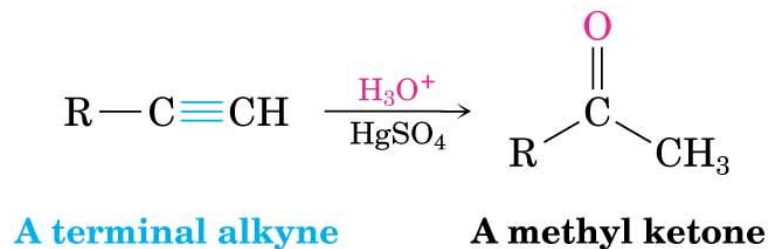
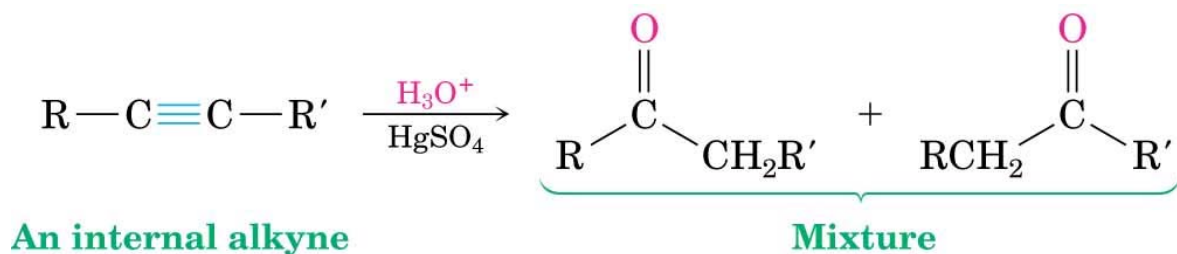
Replacement of  $\text{Hg}^+$  by  $\text{H}^+$  occurs to give a neutral enol.

The enol undergoes tautomerization to give the final ketone product.



# Hydration of Unsymmetrical Alkynes

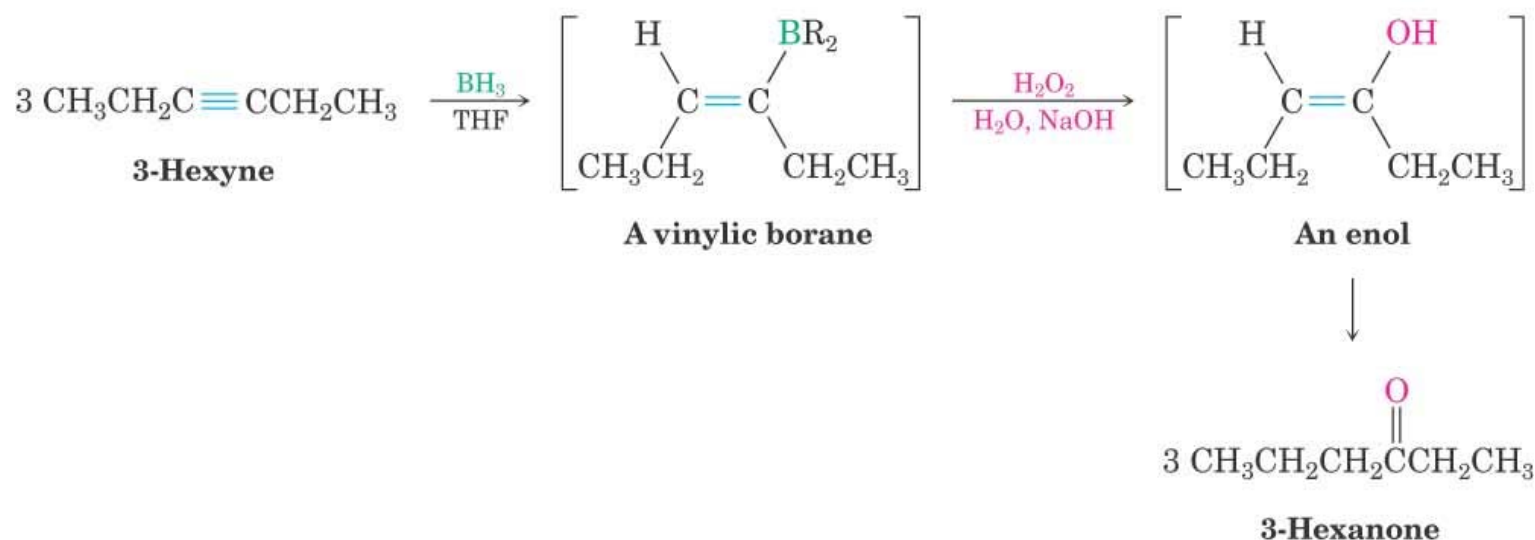
- If the alkyl groups at either end of the C-C triple bond are not the same, both products can form and this is not normally useful
- If the triple bond is at the first carbon of the chain (then H is what is attached to one side) this is called a **terminal** alkyne
- Hydration of a terminal alkyne always gives the methyl ketone, which is useful



# Hydroboration/Oxidation of Alkynes

- $\text{BH}_3$  (borane) adds to alkynes to give a vinylic borane
- Oxidation with  $\text{H}_2\text{O}_2$  produces an enol that converts to the ketone or aldehyde
- Process converts alkyne to ketone or aldehyde with orientation opposite to mercuric ion catalyzed hydration

An internal alkyne





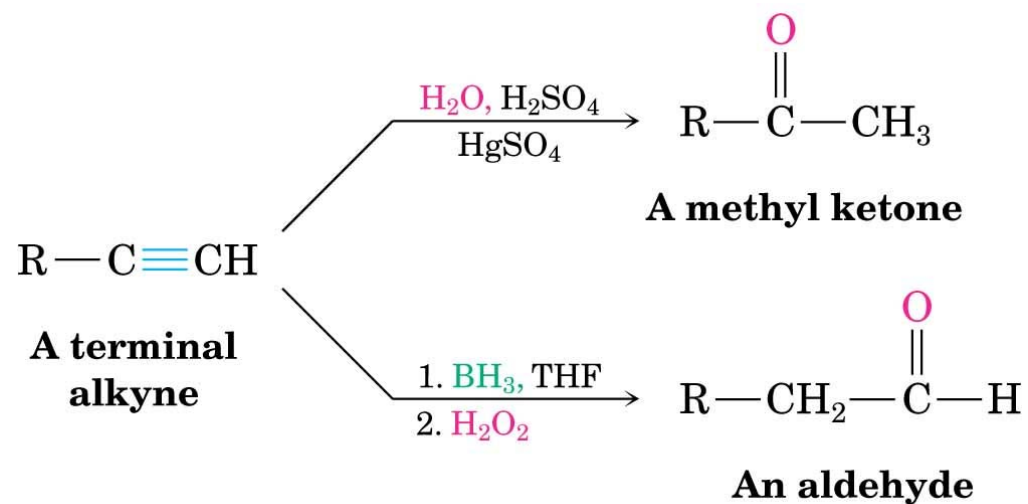
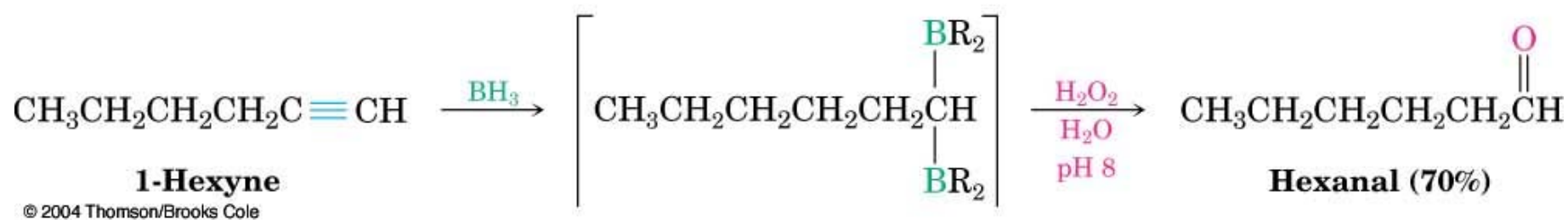
### A terminal alkyne



## Comparison of Hydration of Terminal Alkynes

- Hydroboration/oxidation converts terminal alkynes to aldehydes (terminal CO double bond) because addition of water is anti-Markovnikov
- The product from the mercury (II) catalyzed hydration converts terminal alkynes to methyl ketones (CO double bond sandwiched between two carbon atoms) following Markovnikov's addition rule.

## A terminal alkyne



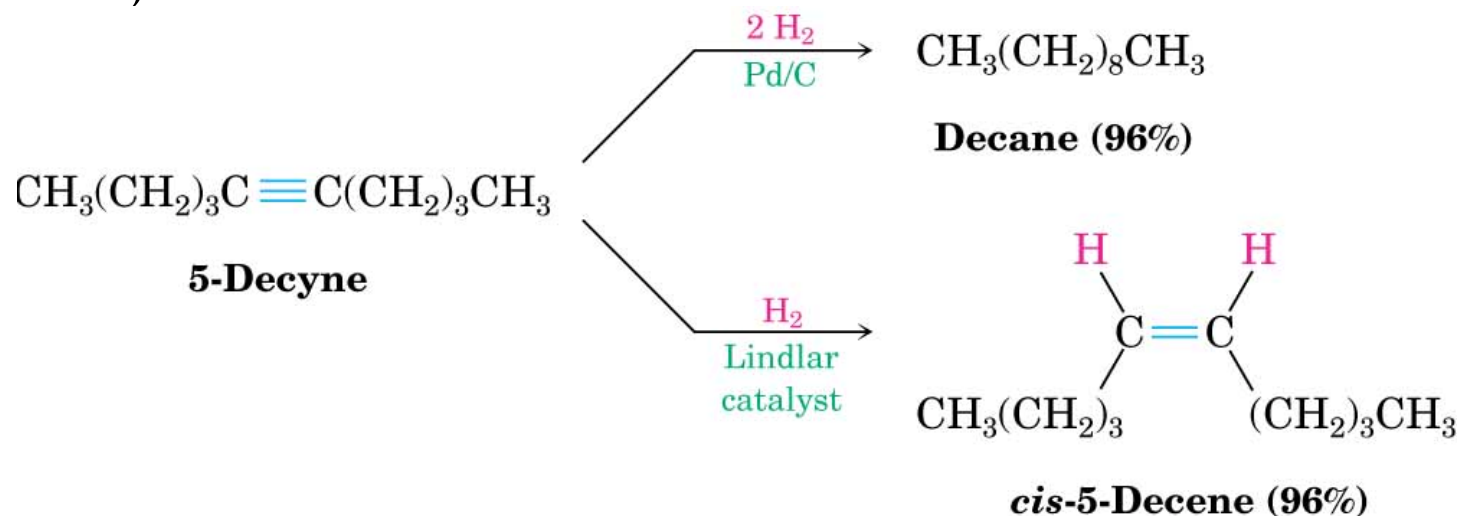
## 8.6 Reduction of Alkynes

- Addition of H<sub>2</sub> over a metal catalyst (such as palladium on carbon, Pd/C) converts alkynes to alkanes (complete reduction)
- The addition of the first equivalent of H<sub>2</sub> produces an alkene, which is more reactive than the alkyne so the alkene is not observed



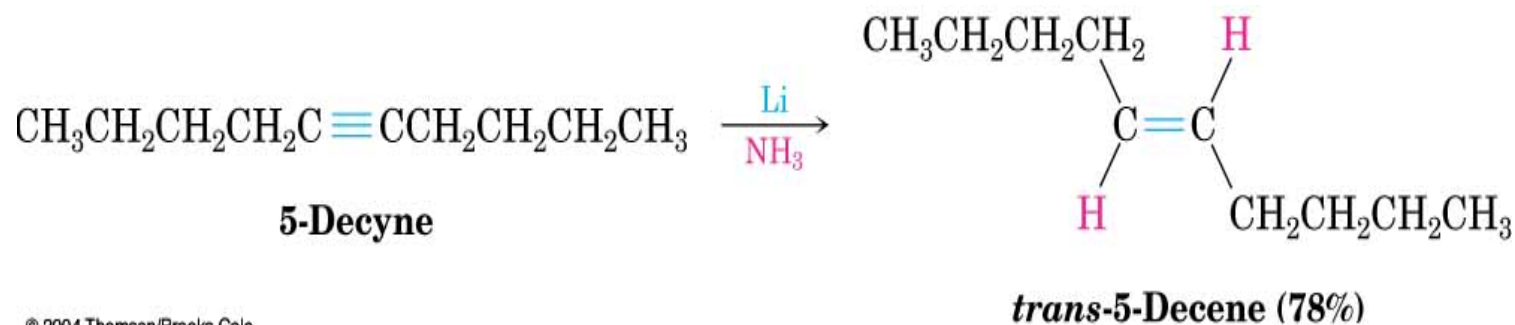
# Conversion of Alkynes to cis-Alkenes

- Addition of  $\text{H}_2$  using chemically deactivated palladium on calcium carbonate as a catalyst (the *Lindlar catalyst*) produces a cis alkene
- The two hydrogens add *syn* (from the same side of the triple bond)



# Conversion of Alkynes to trans-Alkenes

- Anhydrous ammonia (NH<sub>3</sub>) is a liquid below -33 °C
  - Alkali metals dissolve in liquid ammonia and function as reducing agents
- Alkynes are reduced to trans alkenes with sodium or lithium in liquid ammonia
- The reaction involves a *radical anion* intermediate

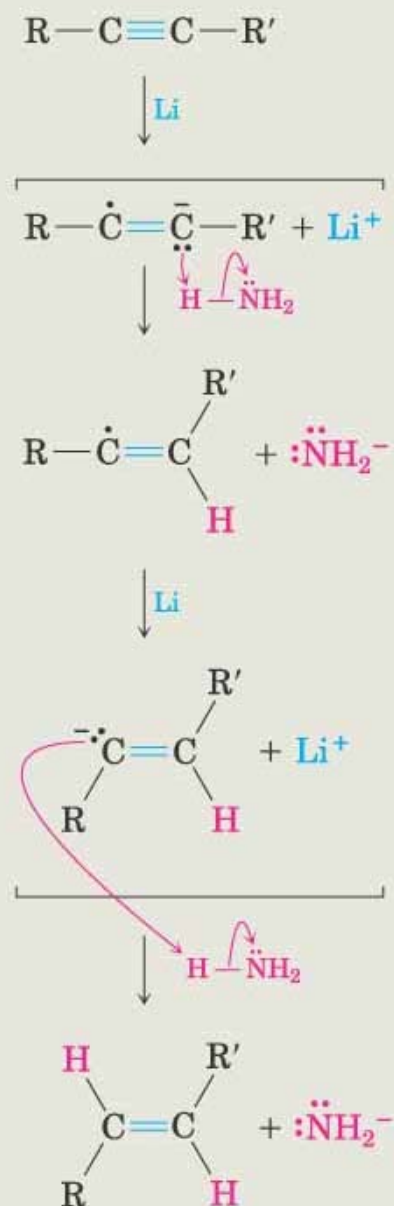


Lithium metal donates an electron to the alkyne to give an anion radical . . .

. . . which abstracts a proton from ammonia solvent to yield a vinylic radical.

The vinylic radical accepts another electron from a second lithium atom to produce a vinylic anion . . .

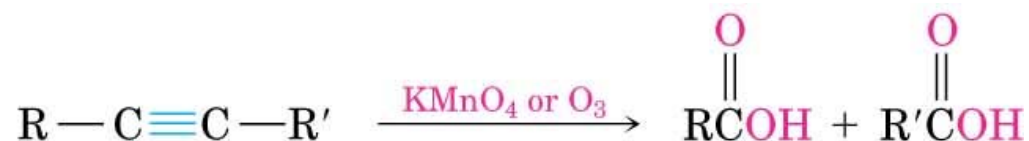
. . . which abstracts another proton from ammonia solvent to yield the final trans alkene product.



## 8.7 Oxidative Cleavage of Alkynes

- Strong oxidizing reagents ( $\text{O}_3$  or  $\text{KMnO}_4$ ) cleave internal alkynes, producing two carboxylic acids
- Terminal alkynes are oxidized to a carboxylic acid and carbon dioxide
- Neither process is useful in modern synthesis – were used to elucidate structures because the products indicate the structure of the alkyne precursor

An internal alkyne




A terminal alkyne



## 8.8 Alkyne Acidity: Formation of Acetylide Anions

- Terminal alkynes are weak Brønsted acids (alkenes and alkanes are much less acidic)  $pK_a \sim 25$ . See Table 8.1 for comparisons.

**TABLE 8.1** Acidity of Simple Hydrocarbons

Type	Example	$K_a$	$pK_a$	
Alkyne	$\text{HC}\equiv\text{CH}$	$10^{-25}$	25	Stronger acid
Alkene	$\text{H}_2\text{C}=\text{CH}_2$	$10^{-44}$	44	
Alkane	$\text{CH}_4$	$\sim 10^{-60}$	60	Weaker acid



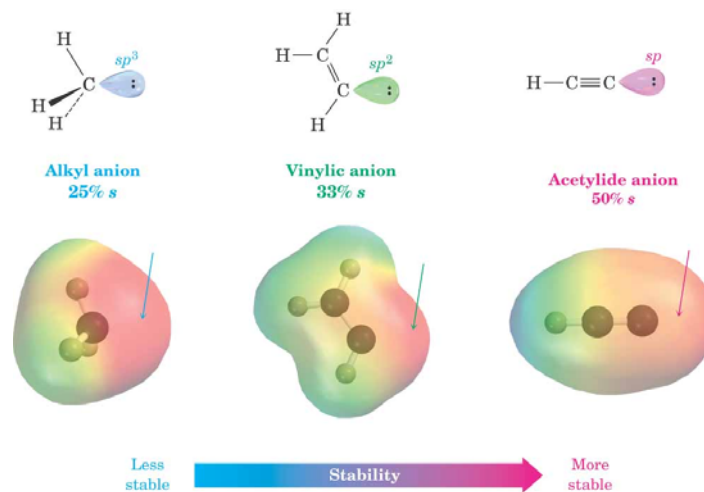
- Reaction of strong anhydrous bases with a terminal acetylene produces an **acetylide ion**



### Acetylide anion

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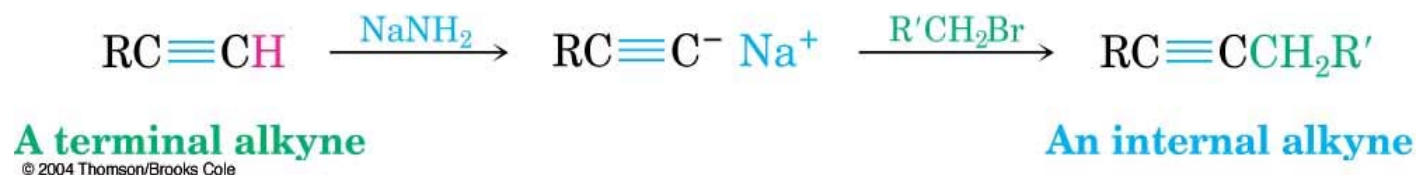
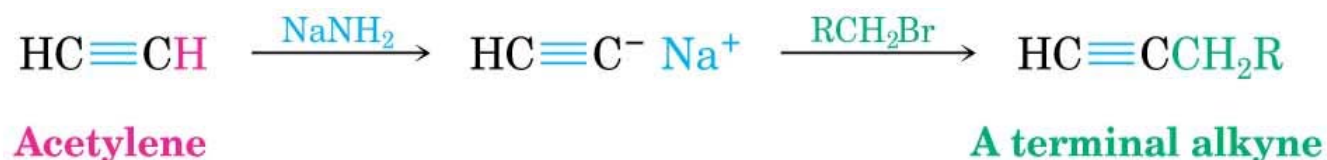
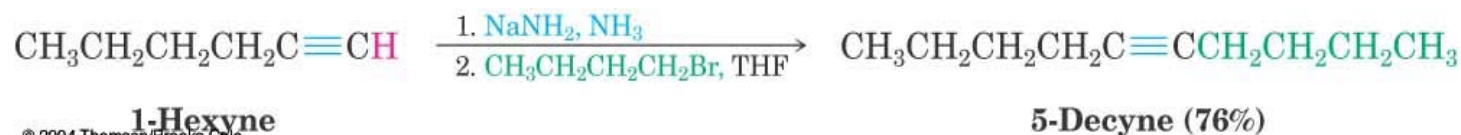
- The  $sp$ -hybridization at carbon holds negative charge relatively close to the positive nucleus



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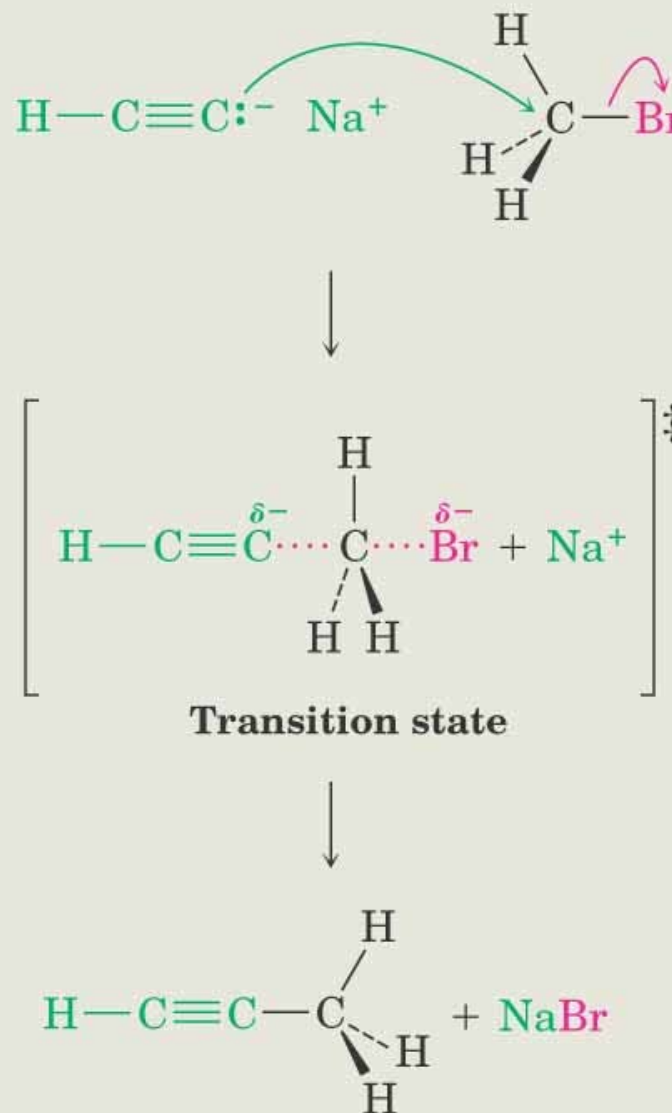
## 8.9 Alkylation of Acetylide Anions

- Acetylide ions can react as nucleophiles as well as bases (see Figure 8-6 for mechanism)
- Reaction with a primary alkyl halide produces a hydrocarbon that contains carbons from both partners, providing a general route to larger alkynes



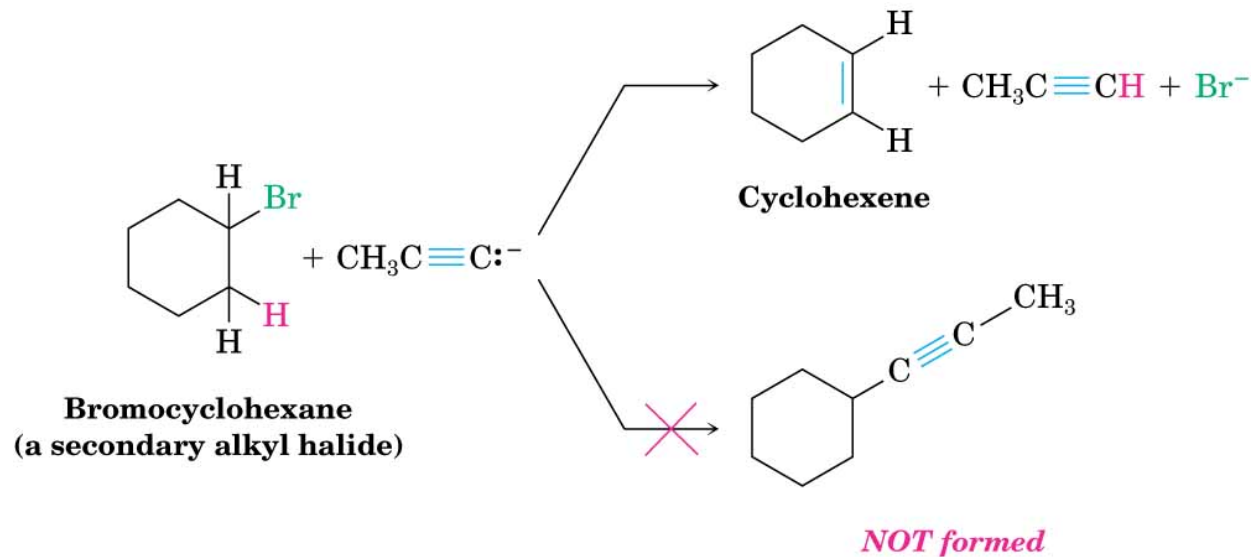
The nucleophilic acetylide anion uses its electron lone pair to form a bond to the positively polarized, electrophilic carbon atom of bromomethane. As the new C–C bond begins to form, the C–Br bond begins to break in the transition state.

The new C–C bond is fully formed and the old C–Br bond is fully broken at the end of the reaction.



# Limitations of Alkylation of Acetylide Ions

- Reactions only are efficient with 1° alkyl bromides and alkyl iodides
- Acetylide anions can behave as bases as well as nucleophiles
- Reactions with 2° and 3° alkyl halides gives dehydrohalogenation, converting alkyl halide to alkene



## 8.10 An Introduction to Organic Synthesis

- Organic synthesis creates molecules by design
- Synthesis can produce new molecules that are needed as drugs or materials
- Syntheses can be designed and tested to improve efficiency and safety for making known molecules
- Highly advanced synthesis is used to test ideas and methods, answering challenges
- Chemists who engage in synthesis may see some work as *elegant* or *beautiful* when it uses novel ideas or combinations of steps – this is very subjective and not part of an introductory course

# Synthesis as a Tool for Learning Organic Chemistry

- In order to propose a synthesis you must be familiar with reactions
  - What they begin with
  - What they lead to
  - How they are accomplished
  - What the limitations are
- A synthesis combines a series of proposed steps to go from a defined set of reactants to a specified product
- - Questions related to synthesis can include partial information about a reaction in a series that the student completes

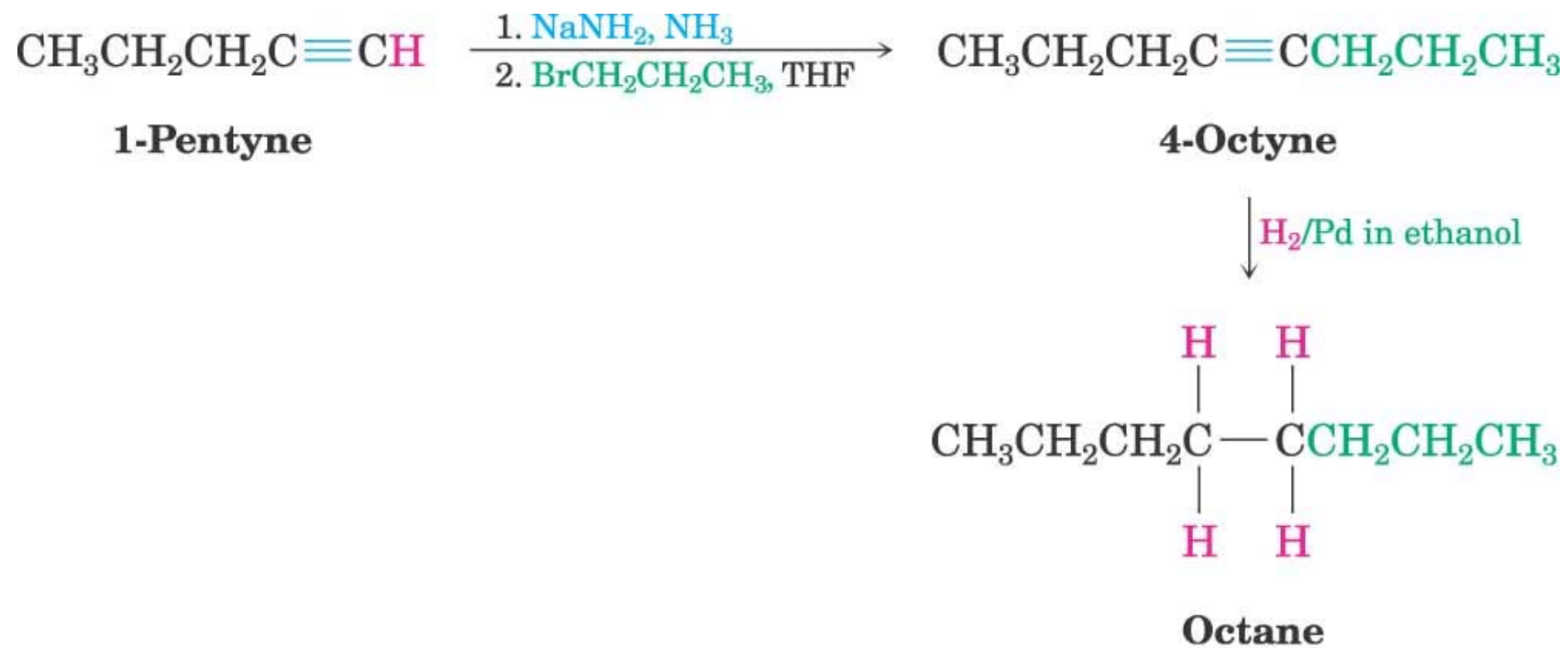
# Strategies for Synthesis

- Compare the target and the starting material
- Consider reactions that efficiently produce the outcome. Look at the product and think of what can lead to it
- Example
  - Problem: prepare octane from 1-pentyne
  - Strategy: use acetylide coupling



**1-Pentyne**

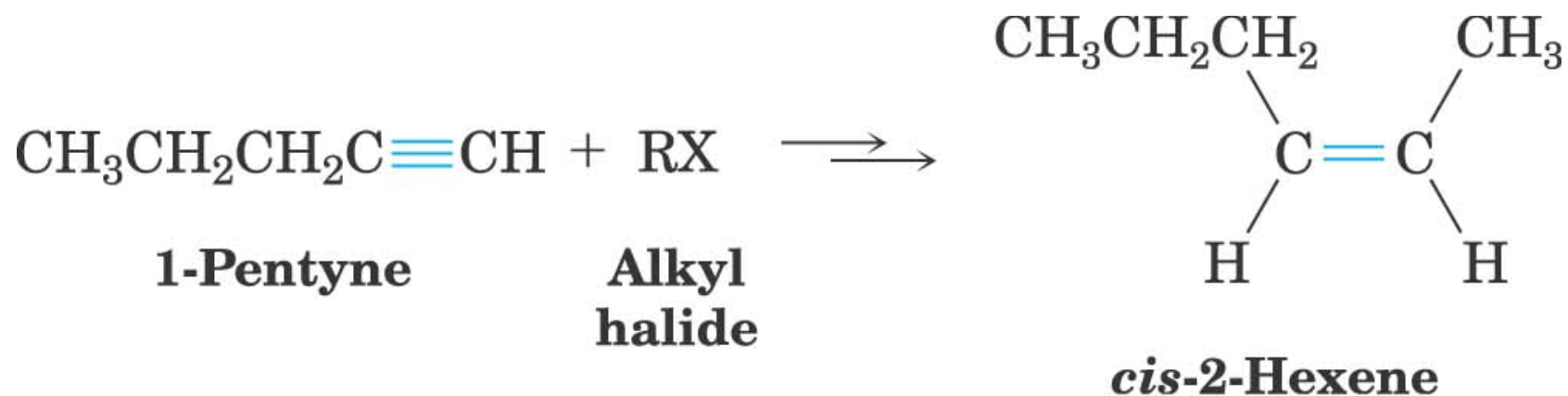
**Octane**



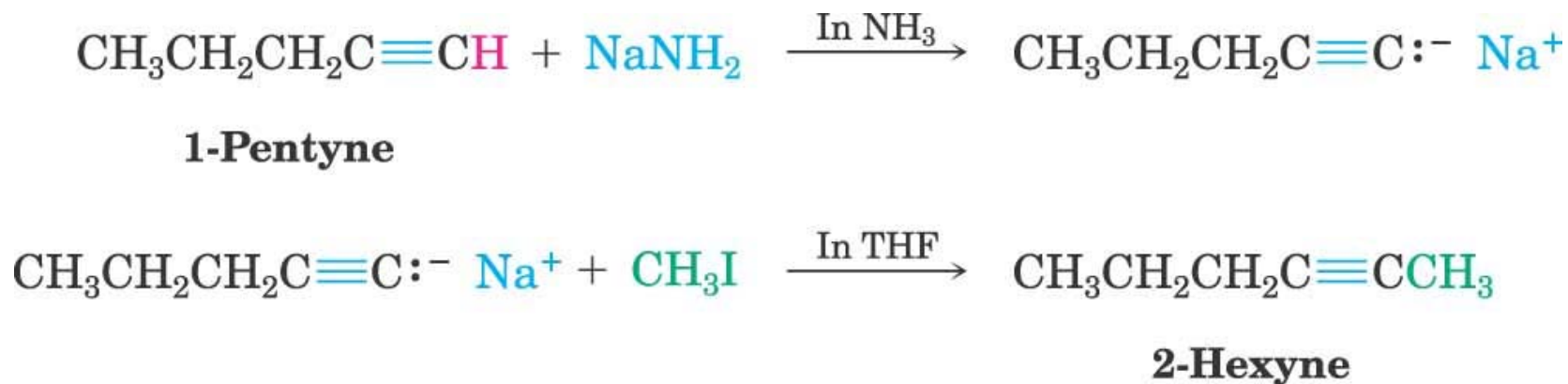
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Prepare cis-2-Hexene starting from 1-pentyne

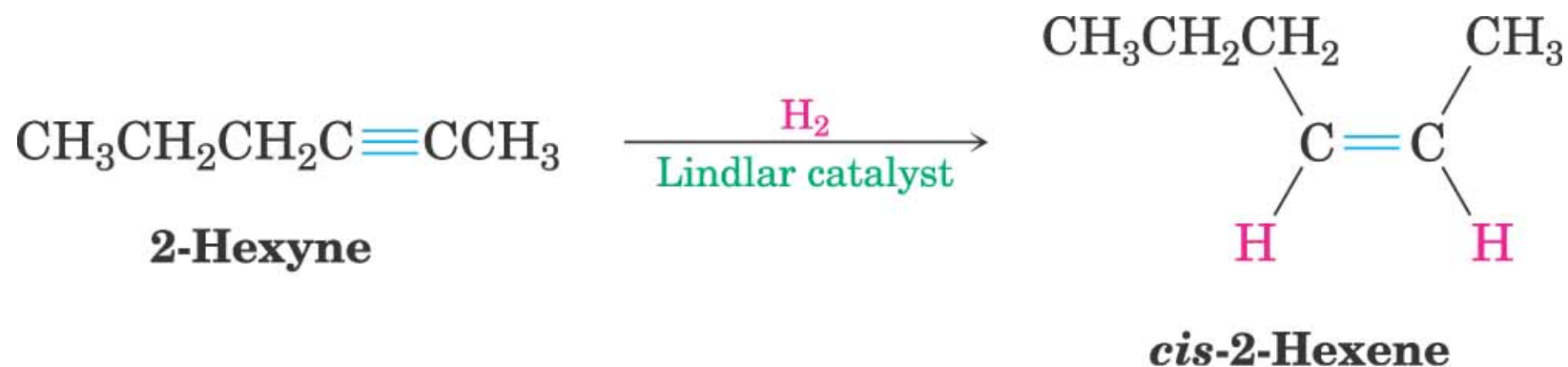




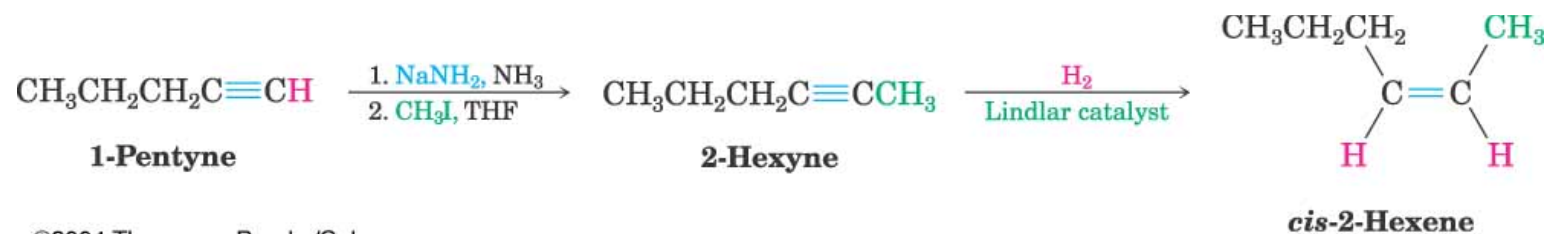
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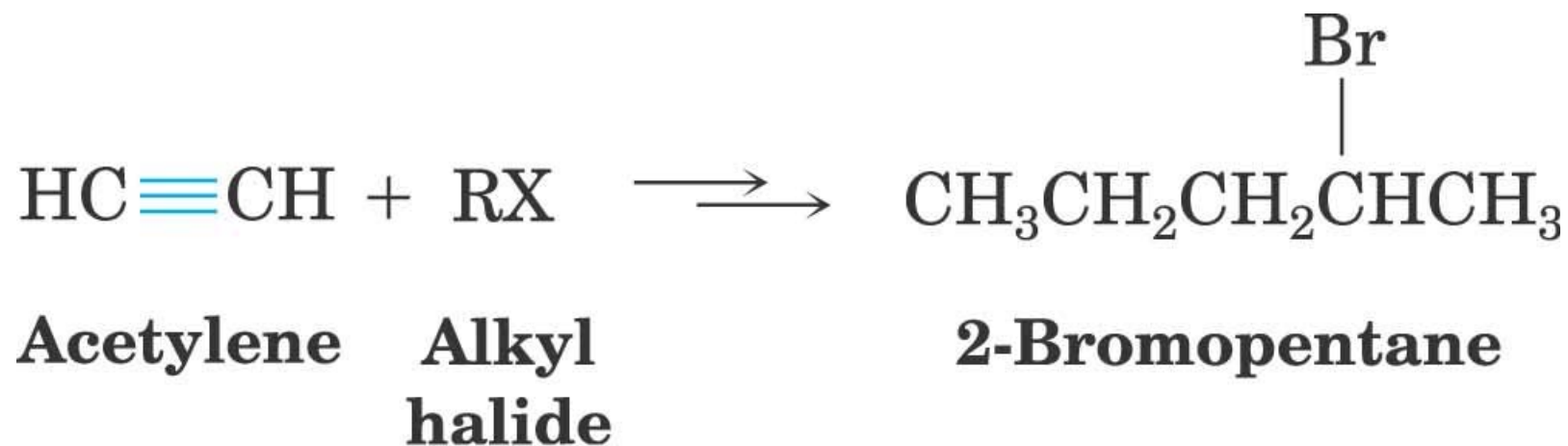
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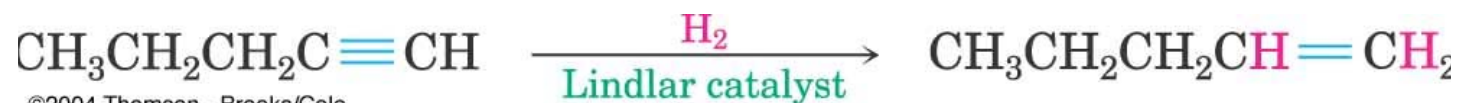
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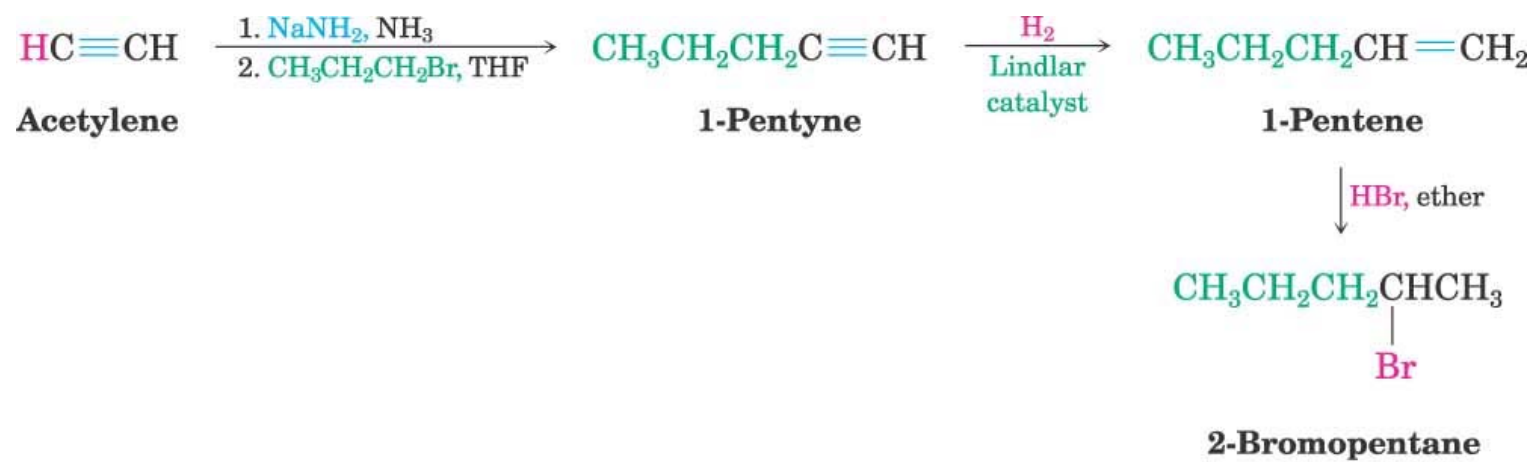
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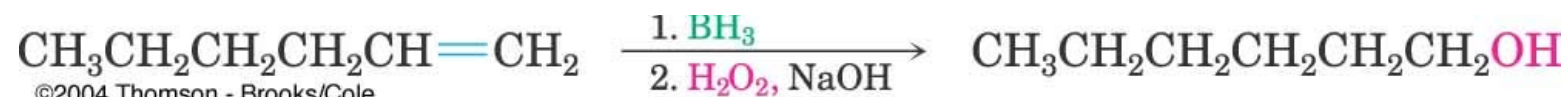


**Acetylene**

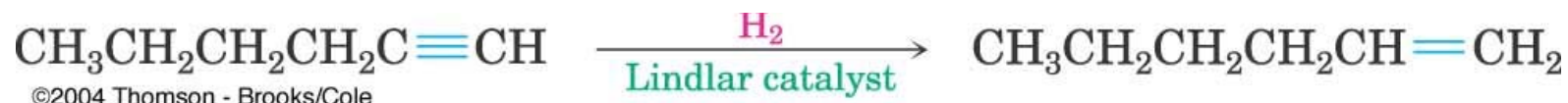
**Alkyl  
halide**

**1-Hexanol**

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