Alkyne
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 alkenes provides an introduction to organic synthesis, the preparation of organic molecules from simpler organic molecules

**physical properties:**
- weakly or non-polar,
- no H-bonding
- relatively low mp/bp
- water insoluble

**Alkynes.** \( C_nH_{2n-2} \)

- \( C_2H_2 \) \( \text{H:C:::C:H} \) \( \text{H—C \equiv C—H} \) \( \text{sp \Rightarrow linear, 180°} \)
  - acetylene (ethylene)

- \( C_3H_4 \) \( \text{CH}_3\text{C}=\text{CH} \) methylacetylene (propyne)
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 $\pi$ bonds.
- The remaining $sp$ orbitals form bonds to other atoms at 180° to C-C triple bond.
- The bond is shorter and stronger than single or double.
- Breaking a $\pi$ bond in acetylene (HCCH) requires 202 kJ/mole (in ethylene it is 269 kJ/mole)
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 is assigned to the first carbon of the triple bond.

\[ \text{CH}_3\text{CH}_2\text{CHCH}_2\text{C}≡\text{CCH}_2\text{CH}_3 \]

Begin numbering at the end nearer the triple bond.

**6-Methyl-3-octyne**

(New: 6-Methylpent-3-yne)

**1-Hepten-6-yne**

(New: Hept-1-en-6-yne)

**4-Methyl-7-nonen-1-yne**

(New: 4-Methylnon-7-en-1-yne)

**Butyl**

(an alkyl group)

**1-Butenyl**

(a vinylic group)

**1-Butynyl**

(an alkyne group)

(New: But-1-enyl)

(New: But-1-ynyl)
Nomenclature:

common names: “alkylacetylene”

IUPAC: parent chain = longest continuous carbon chain that contains the triple bond.

alkane drop –ane add -yne

prefix locant for the triple bond, etc.

\[
\text{CH}_3\text{CH}_2\text{C}≡\text{CCH}_3 \quad 2\text{-pentyne ( ethylmethylacetylene)}
\]

“terminal” alkynes have the triple bond at the end of the chain:

\[
\begin{align*}
\text{CH}_3 \\
\text{CH}_3\text{CH}_2\text{C}≡\text{CH} & \quad \text{HC}≡\text{CCHCH}_2\text{CH}_3 \\
1\text{-butyne} & \quad 3\text{-methyl-1-pentyne} \\
\text{ethylacetylene} & \quad \text{sec-butylacetylene}
\end{align*}
\]
9.2 Preparation of Alkynes: Elimination Reactions of Dihalides

- Treatment of a 1,2-dihaloalkane with KOH or NaOH produces a two-fold elimination of HX.
- Vicinal dihalides are available from addition of bromine or chlorine to an alkene.
- Intermediate is a vinyl halide.

Chemical reactions:

1. **1,2-Diphenylethyne (Stilbene)**
   - Reaction with HBr, CH$_2$Cl$_2$.

2. **1,2-Dibromo-1,2-diphenylethane**
   - Reaction with KOH, ethanol.

3. **Diphenylacetylene (85%)**
   - Reaction with H$_2$O, KBr.

4. **(Z)-3-Chloro-2-buten-1-ol**
   - Reaction with 1.2 NaNH$_2$, 2. H$_3$O$^+$.
   - Product: CH$_3$C≡CCH$_2$OH (2-Butyn-1-ol).
9.2 Preparation of Alkynes:
Elimination Reactions of Dihalides

Dehydrohalogenation - Remove of HX

* Alkynes can be produced by removing 2 molecules of HX
  → Requires strong base

R - C - C - R'  →  R - C - C - R'

Vicinal     Geminal

Remove 1 HX → alkene (vinyl halide)

Remove 2 HX → alkyne
9.2 Preparation of Alkynes: Elimination Reactions of Dihalides

- Works with vicinal or geminal dihalides
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9.2 Preparation of Alkynes: Elimination Reactions of Dihalides

- For geminal dihalides (on C2), can produce either internal or terminal alkyne
Synthesis, alkynes:

1. dehydrohalogenation of vicinal dihalides

\[ \begin{align*}
\text{H} & \quad \text{H} \\
\mid & \quad \mid \\
\text{C} & \quad \text{C} \quad + \text{KOH} \quad \Rightarrow \\
\mid & \quad \mid \\
\text{X} & \quad \text{X} \\
\text{H} & \quad \mid \quad \mid \\
\text{C} = \text{C} & \quad + \text{KX} + \text{H}_2\text{O} \\
\mid & \quad \mid \\
\text{X} & \\
\text{H} & \quad \mid \quad \mid \\
\text{C} = \text{C} & \quad + \text{NaNH}_2 \quad \Rightarrow \\
\mid & \quad \mid \\
\text{X} & \\
\end{align*} \]
\[
\begin{align*}
\text{CH}_3\text{CH}_2\text{CHCH}_2 \quad \text{+ KOH; then NaNH}_2 & \rightarrow \text{CH}_3\text{CH}_2\text{C}≡\text{CH} \\
\text{Br} \quad \text{Br} & \quad \text{“ + 2 KOH, heat}
\end{align*}
\]
alkene $\rightarrow$ vicinal dihalide $\xrightarrow{1. KOH}$ alkyne

$\text{CH}_3\text{CH}=\text{CH}_2 \xrightarrow{\text{Br}_2} \text{CH}_3\text{CHCH}_2\text{Br} \xrightarrow{1. KOH}$ $\xrightarrow{2. \text{NaNH}_2} \text{CH}_3\text{C}=\text{CH}$
Synthesis of propyne from propane

\[
\text{CH}_3\text{CH}_2\text{CH}_3 + \text{Br}_2, \text{heat} \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2-\text{Br} + \text{CH}_3\text{CHCH}_3\text{Br}
\]

\[
\text{KOH(alc)} \rightarrow \text{CH}_3\text{CHCH}_2\text{Br} \rightarrow \text{CH}_3\text{CH=CH}_2
\]

\[
\text{KOH} \rightarrow \text{CH}_3\text{CH=CH}_2 + \text{Br}_2 \rightarrow \text{CH}_3\text{C}=\text{CH}
\]

\[
\text{NaNH}_2 \rightarrow \text{CH}_3\text{C}=\text{CH}
\]
2. coupling of metal acetylides with 1°/CH₃ alkyl halides

\[
R-\text{C}≡\text{C}^+\text{Na}^+ + R´X \rightarrow R-\text{C}≡\text{C}R´ + \text{NaX}
\]

a) \( S_N^2 \)

b) \( R´X \) must be 1° or CH₃X

\[
\text{CH}_3\text{C}≡\text{C}^+\text{Li}^+ + \text{CH}_3\text{CH}_2\text{-Br} \rightarrow \text{CH}_3\text{C}≡\text{C}\text{CH}_2\text{CH}_3
\]
note: R-X must be 1\textdegree{} or CH\textsubscript{3} to get S\textsubscript{N}2!

\[
\text{CH}_3\text{C}≡\text{C}^- \text{Na}^+ + \text{CH}_3\text{C}\text{CH}_3\text{Br} \rightarrow \text{CH}_3\text{C}≡\text{CH}_2 + \text{CH}_3\text{C}≡\text{CH}
\]

3\textdegree{} alkyl halide
E2 elimination!
<table>
<thead>
<tr>
<th>alkynes</th>
<th>terminal only</th>
</tr>
</thead>
<tbody>
<tr>
<td>acids</td>
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</tr>
<tr>
<td>bases</td>
<td>✓ some</td>
</tr>
<tr>
<td>metals</td>
<td>✓</td>
</tr>
<tr>
<td>oxid.</td>
<td>✓</td>
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<tr>
<td>reduct.</td>
<td>✓</td>
</tr>
<tr>
<td>halogens</td>
<td>✓</td>
</tr>
</tbody>
</table>
Reactions, alkynes:

1. addition of H$_2$ (reduction)
2. addition of X$_2$
3. addition of HX
4. addition of H$_2$O, H$^+$
5. as acids
6. Ag$^+$
7. oxidation
9.3 Reactions of Alkynes: Addition of HX and X₂

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

\[
\text{CH}_3\text{CH}_2\text{C≡CH} \xrightarrow{\text{Br}_2, \text{CH}_2\text{Cl}_2} \text{Br} \text{Br} \text{C} \begin{array}{c} \text{H} \\ \text{CH}_3\text{CH}_2 \end{array} \xrightarrow{\text{Br}_2, \text{CH}_2\text{Cl}_2} \text{Br} \text{Br} \text{C} \begin{array}{c} \text{H} \\ \text{CH}_3\text{CH}_2 \end{array} \xrightarrow{\text{Br}_2, \text{CH}_2\text{Cl}_2} \text{Br} \text{Br} \text{C} \begin{array}{c} \text{H} \\ \text{CH}_3\text{CH}_2 \end{array}
\]

1-Butyne \quad (E)-1,2-Dibromo-1-butene \quad 1,1,2,2-Tetrabromobutane
Addition of Bromine and Chlorine

- Initial addition gives *trans* intermediate
- Product with excess reagent is tetrahalide

\[
\begin{align*}
\text{CH}_3\text{CH}_2\text{C} \equiv \text{CH} & \quad \xrightarrow{\text{Br}_2/\text{CH}_2\text{Cl}_2} \quad \text{C} \equiv \text{C} & \quad \xrightarrow{\text{Br}_2/\text{CH}_2\text{Cl}_2} \quad \text{CH}_3\text{CH}_2\text{C} - \text{CH} \\
\text{1-Butyne} & & (E)-1,2-\text{Dibromo-1-butene} & & 1,1,2,2-\text{Tetrabromobutane}
\end{align*}
\]
Addition of HX to Alkynes Involves Markovnikov Products

Internal alkynes produce mixture of halogenated alkenes, then Markovnikov product

$$\text{CH}_3\text{CH}_2\text{C}≡\text{CCH}_2\text{CH}_3 + \text{HCl} → \text{CH}_3\text{CH}_2\text{C}≡\text{CCH}_2\text{CH}_3$$

3-Hexyne

$$\text{CH}_3\text{CH}_2\text{C}≡\text{CCH}_2\text{CH}_3 + \text{HCl} → \text{CH}_3\text{CH}_2\text{C}═\text{CCH}_2\text{CH}_3$$

(Z)-3-Chloro-3-hexene

Terminal alkynes produce Markovnikov product

$$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CH} + \text{HBr} → \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CH}$$

1-Hexyne

$$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CH} + \text{HBr} → \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CH}$$

2-Bromo-1-hexene

$$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CH} + \text{HBr} → \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CH}$$

2,2-Dibromohexane
Hydration of Alkynes

- Addition of H-OH as in alkenes
  - Mercury (II) catalyzes Markovnikov oriented addition
  - Hydroboration-oxidation gives the anti-Markovnikov product

\[
\begin{align*}
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}\equiv\text{CH} & \xrightarrow{\text{H}_2\text{O, H}_2\text{SO}_4, \text{HgSO}_4} \left[\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}\equiv\text{CH}\right] & \xrightarrow{} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{C}\equiv\text{CH} \\
\text{1-Hexyne} & & \text{2-Hexanone (78\%)}
\end{align*}
\]
Mercury(II)-Catalyzed Hydration of Alkynes

- Alkynes do not react with aqueous protic acids
- Mercuric ion (as the sulfate) is a Lewis acid catalyst that promotes addition of water with Markovnikov orientation
- The immediate product is a vinylic alcohol, or enol, which spontaneously transforms to a ketone or to an aldehyde in the event that acetylene is employed.
Mechanism of Mercury(II)-Catalyzed Hydration of Alkynes

- Addition of Hg(II) to alkyne gives a vinylic cation
- Water adds and loses a proton
- A proton from aqueous acid replaces Hg(II)

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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.

\[
\begin{align*}
\text{Enol tautomer} & \quad \longleftrightarrow \quad \text{Keto tautomer} \\
\text{(less favored)} & \quad \text{(more favored)}
\end{align*}
\]

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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.

### An internal alkyne

\[
R\text{C}≡\text{C}R' \xrightarrow{\text{H}_3\text{O}^+ / \text{HgSO}_4} R\text{C}\text{CH}_2\text{R}' + \text{RCH}_2\text{C}R'
\]

### A terminal alkyne

\[
R\text{C}≡\text{C}H \xrightarrow{\text{H}_3\text{O}^+ / \text{HgSO}_4} R\text{C}\text{CH}_3
\]

A methyl ketone
Hydroboration/Oxidation of Alkynes

- BH₃ (borane) adds to alkynes to give a vinylic borane
- Oxidation with H₂O₂ 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
Comparison of Hydration of Terminal Alkynes

- Hydroboration/oxidation converts terminal alkynes to aldehydes because addition of water is anti-Markovnikov
- The product from the mercury(II) catalyzed hydration converts terminal alkynes to methyl ketones

A terminal alkyne

\[
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CH} \xrightarrow{\text{BH}_3, \text{THF}} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}≡\text{B} \xrightarrow{\text{H}_2\text{D}_2, \text{H}_2\text{O}, \text{pH} 8} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH} \xrightarrow{\text{H}_2\text{O}, \text{H}_2\text{SO}_4, \text{HgSO}_4} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{C}≡\text{CH} \xrightarrow{1. \text{BH}_3, \text{THF}, 2. \text{H}_2\text{O}_2} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}≡\text{CH} \xrightarrow{\text{H}_2\text{O}, \text{H}_2\text{SO}_4, \text{HgSO}_4} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}≡\text{C}≡\text{C}≡\text{H}
\]

1-Hexyne

Hexanal (70%)

An aldehyde

A methyl ketone
Reduction of Alkynes

- Addition of $\text{H}_2$ over a metal catalyst (such as palladium on carbon, Pd/C) converts alkynes to alkanes (complete reduction).

- The addition of the first equivalent of $\text{H}_2$ produces an alkene, which is more reactive than the alkyne so the alkene is not observed.

$$\text{H}_2\text{C}≡\text{CH} \xrightarrow{\text{H}_2, \text{Catalyst}} \text{H}_2\text{C}═\text{CH}_2 \quad \Delta H^\circ_{\text{hydrog}} = -176 \text{ kJ/mol (}-42 \text{ kcal/mol)}$$

$$\text{H}_2\text{C}═\text{CH}_2 \xrightarrow{\text{H}_2, \text{Catalyst}} \text{CH}_3═\text{CH}_3 \quad \Delta H^\circ_{\text{hydrog}} = -137 \text{ kJ/mol (}-33 \text{ kcal/mol)}$$
Conversion of Alkynes to cis-Alkenes

- Addition of 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).

\[
\text{CH}_3\text{CH}_2\text{CH}_2\text{C}≡\text{CCH}_2\text{CH}_2\text{CH}_3 \xrightarrow{\text{H}_2} \xrightarrow{\text{H}_2}\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 \text{ cis-4-Octene Pd/C catalyst} \rightarrow \text{Octane}
\]
Conversion of Alkynes to trans-Alkenes

- Anhydrous ammonia (NH₃) 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

\[
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C≡CCH}_2\text{CH}_2\text{CH}_2\text{CH}_3 \xrightarrow{\text{Li, NH}_3} \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{H} \quad \text{C} = \text{C} \quad \text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3
\]

5-Decyne

trans-5-Decene (78%)
Mechanism of Li/NH$_3$ Reduction of an Alkyne

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

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

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

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

A trans alkene
Oxidative Cleavage of Alkynes

- Strong oxidizing reagents (O$_3$ or KMnO$_4$) cleave internal alkynes and terminal alkynes.
- Neither process is useful in modern synthesis – were used to elucidate structures because the products indicate the structure of the alkyne precursor.
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 9.1 for comparisons))
- Reaction of strong anhydrous bases (e.g., sodium amide) with a terminal alkyne produces an **acetylide ion**
- The $sp$-hybridization at carbon holds negative charge relatively close to the positive nucleus (Figure 9.5 in text)

$\text{R} \equiv \text{C} \equiv \text{C} \equiv \text{H} \overset{\text{NH}_2 \text{ Na}^+}{\rightarrow} \text{R} \equiv \text{C} \equiv \text{C} \equiv \text{Na}^+ + \cdot \text{NH}_3$

* A terminal alkyne  
* An acetylide anion
Alkylation of Acetylide Anions

- Acetylide ions can react as nucleophiles as well as bases (see Figure 9-6 for mechanism)
- Reaction with a primary alkyl halide produces a hydrocarbon that contains carbons from both partners, providing a general route to larger alkynes

\[
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CH} \quad 1. \text{NaNH}_2, \text{NH}_3 \quad \text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{C}≡\text{CCH}_2\text{CH}_2\text{CH}_2\text{CH}_3 \quad 5\text{-Decyne (76%)}
\]

1-Hexyne

\[
\text{H}≡\text{C}≡\text{C}≡\text{H} \quad \text{NaNH}_2 \quad [\text{H}≡\text{C}≡\text{C}^-] \quad \text{RCH}_2\text{Br} \quad \text{H}≡\text{C}≡\text{C}≡\text{CH}_2\text{R} \quad \text{A terminal alkyne}
\]

Acetylene

\[
\text{R}≡\text{C}≡\text{C}≡\text{H} \quad \text{NaNH}_2 \quad [\text{R}≡\text{C}≡\text{C}^-] \quad \text{R'}\text{CH}_2\text{Br} \quad \text{R}≡\text{C}≡\text{C}≡\text{CH}_2\text{R'} \quad \text{An internal alkyne}
\]
Limitations of Alkylation of Acetylide Ions

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

\[
\text{Bromocyclohexane} \quad (\text{a secondary alkyl halide})
\]

\[
\begin{align*}
\text{Bromocyclohexane} + \text{CH}_3\text{C}≡\text{CH}^- \text{Na}^+ & \rightarrow \text{Cyclohexene} + \text{CH}_3\text{C}≡\text{CH} + \text{NaBr} \\
\text{Not formed}
\end{align*}
\]
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 of 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
- Read the practice problems in the text
Let’s Work a Problem

Prepare \( n \)-octane from 1-pentyne.

The best strategy to approach this problem is to use acetylide coupling:

\[
\begin{align*}
\text{1-Pentyne} & \rightarrow \\
\text{4-Octyne} & \\
\text{Octane} & \\
\text{CH}_3\text{CH}_2\text{CH}_2\text{C}≡\text{CH} & \rightarrow \\
\text{CH}_3\text{CH}_2\text{C}≡\text{CCH}_2\text{CH}_2\text{CH}_3 & \text{1. NaNH}_2, \text{ NH}_3 \\
& \text{2. BrCH}_2\text{CH}_2\text{CH}_3, \text{ THF} \\
& \text{H}_2/\text{Pd in ethanol}
\end{align*}
\]