TOPIC 9. CONJUGATED SYSTEMS AND AROMATICITY

OBJECTIVES

1. Describe the interaction of alkenes with adjacent p-orbitals.

2. Discuss the influence of this interaction on the chemistry of dienes (relative to alkenes)

3. Describe the influence of conjugation on the ease of formation of carbocations and radicals (relative to alkyl radicals) and carbocations

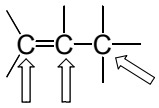
4. Contrast the structure and reactivity of alkenes and benzene

5. Provide a theoretical basis for aromaticity: the observation that compounds with a benzene ring are particularly stable

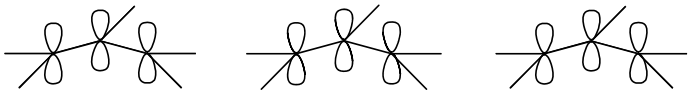
6. Recognize that antiaromatic compounds are unstable

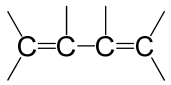
INTRODUCTION

Alkenes undergo addition chemistry. However, alkenes also influence the reactivity of adjacent sp^3 "allylic" carbons.



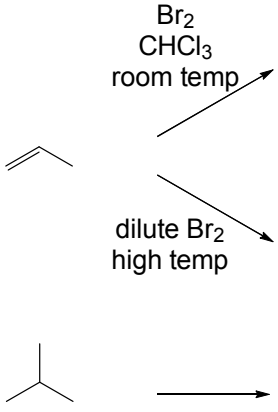
p-orbitals adjacent to a cation, anion, radical, or alkene influence each other and are said to be "conjugated" (*verb:* to join together, as in marriage)





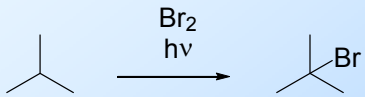
ALLYLIC AND BENZYLIC RADICALS

Bromination



PRS

What type of reactive intermediate is formed in the bromination of alkanes?



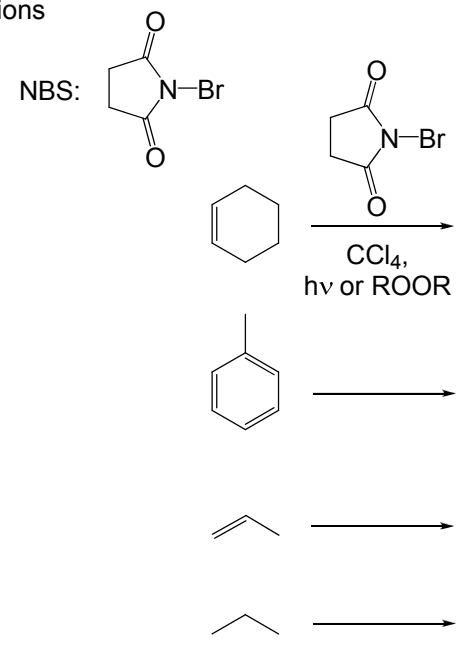
1 cation

2 anion

3 radical

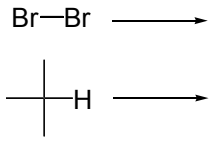
4 carbene

N-Bromosuccinimide (NBS) is a useful reagent for allylic and benzylic brominations

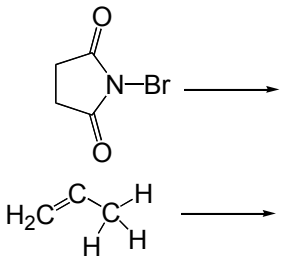


Mechanism

Review of Radical Bromination of Alkanes



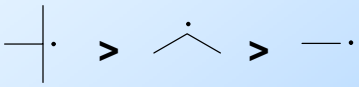
Bromination of Allylic and Benzylic Positions: Influence of a Double Bond



⇒

PRS

Which of the following explains the relative stability of alkyl radicals?



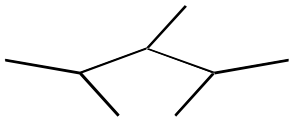
1 conjugation

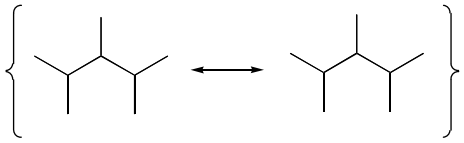
2 resonance

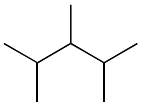
3 hyperconjugation

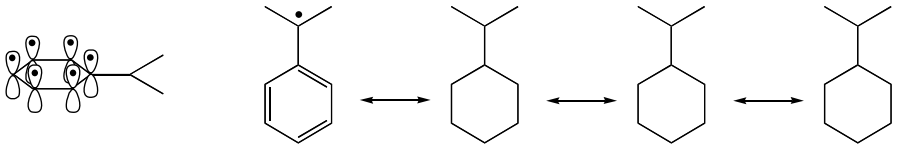
4 hybridization

The Stability of the Allylic and Benzylic Radicals

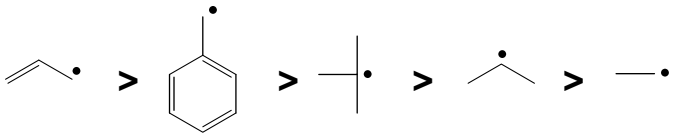








Stability of radicals (and ease of formation)



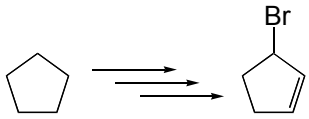
allylic benzylic 3° 2° 1°

Consequence of Resonance Stabilization of Intermediate Radicals – Formation of Regioisomers

Problem [Solomons 13.36] – What are the four isomers with formula C_5H_9Br formed by the reaction of 1-pentene with NBS?

?

[Solomons Problem 13.22e] - How would you carry out the following transformation? (several steps may be necessary)



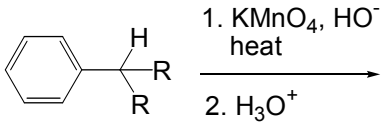
?

? *Prob:*13.1,22,36 ?

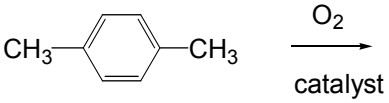
L3

Oxidation of Benzylic Positions

In laboratory



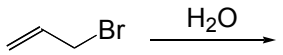
In industry

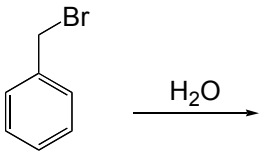


Oxidation of p-xylene to terephthalic acid
for production of polyester

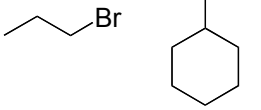
ALLYLIC AND BENZYLIC CARBOCATIONS

Propenyl bromide (allyl bromide) and benzylic bromides undergoes rapid hydrolysis to form the corresponding alcohols





compare:

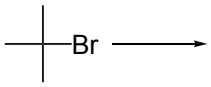


quite unreactive

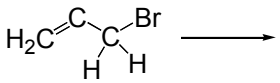
Previously we have seen that hydrolysis of tertiary alkyl bromides by an S_N1 mechanism via a tertiary carbocation

Mechanism

Review of Hydrolysis (S_N1 reaction with H_2O) of tert-Butyl Halides



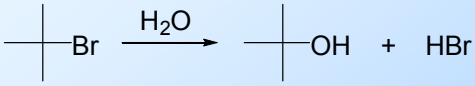
Hydrolysis Allylic and Benzylic Positions: Influence of a Double Bond



⇒

PRS

What type of reactive intermediate is formed in the bromination of alkanes?



1 cation

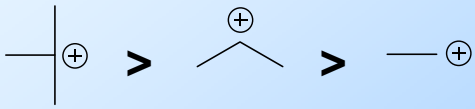
2 anion

3 radical

4 carbene

PRS

Which of the following explains the stability of alkyl carbocations?



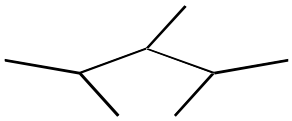
1 conjugation

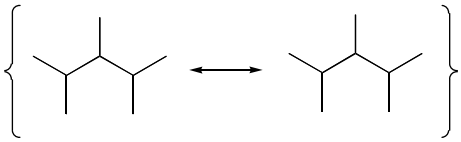
2 resonance

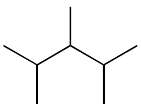
3 hyperconjugation

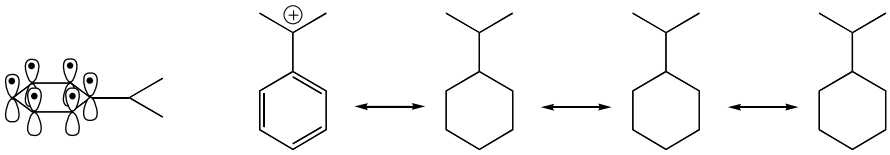
4 hybridization

The Stability of the Allylic and Benzylic Carbocations

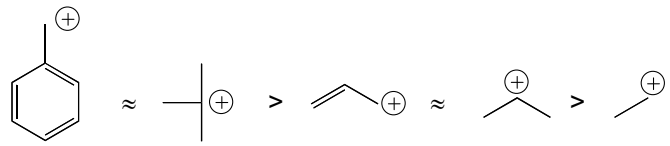






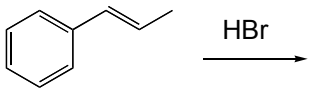


Stability (and ease of formation):



benzylic 3° allylic 2° 1°

Carbocations are also formed by the protonation of alkenes (e.g., in the addition of HBr and H_2O/H^+). The enhanced stability of allylic and benzylic cations can be used to explain the regiochemistry of addition reactions.



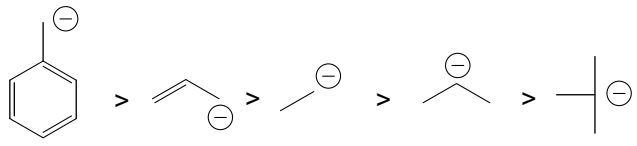
Consequences of the enhanced stability of allylic and benzylic cations by resonance include:

- Mild *nucleophilic substitution* reactions of allyl and benzyl halides (via more stable carbocation)

- Regiochemistry of *electrophilic addition* to alkenyl benzenes (via more stable carbocation)

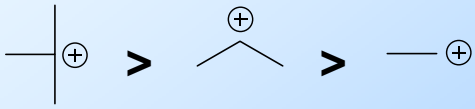
A brief note about anions

Stability (ease of formation):



PRS

Which of the following explains the stability of alkyl carbocations?



1 conjugation

2 resonance

3 hyperconjugation

4 hybridization

PRS

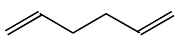
Problem [Solomons 13.33] – What are the ***four*** products with molecular formula C_4H_7Cl formed upon treatment of $CH_3CH{=}CHCH_2OH$ with HCl?

?

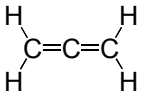
? *Prob:* 1.4,32 ?

ALKADIENES AND POLYUNSATURATED HYDROCARBONS

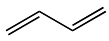
Classes of dienes



1,5-hexadiene
an isolated diene; the
alkenes react independently



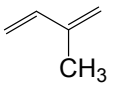
1,2-propadiene
a cumulated diene; not common



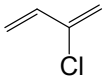
1,3-butadiene
a conjugated diene;
⇒ *alkenes influence one another*

CONJUGATED DIENES

Examples



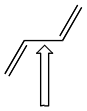
isoprene
monomer of natural rubber



chloroprene
monomer of neoprene

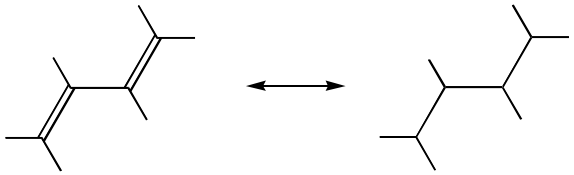
The effect of conjugation on the structure of dienes

$H_3C–CH_3$	1.54 Å
$H_2C=CH_2$	1.34 Å
$HC\equiv CH$	1.20 Å



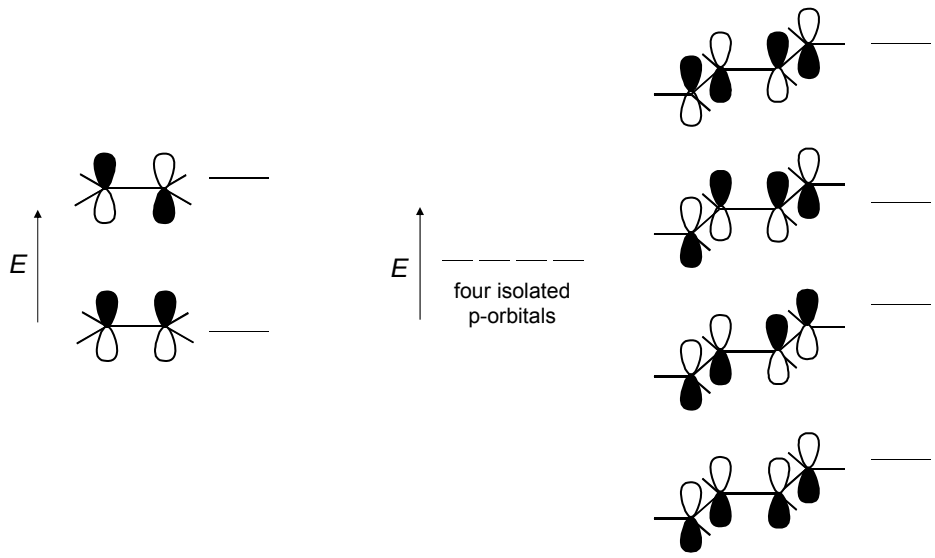
1.47 Å

Resonance in Conjugated Dienes



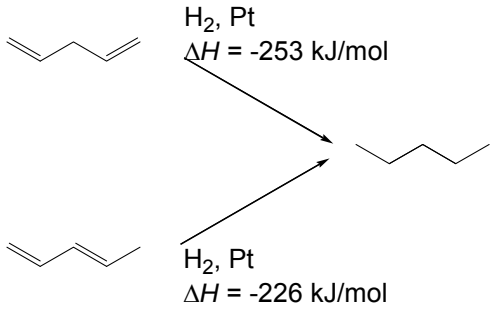
A Molecular Orbital Description of Butadiene

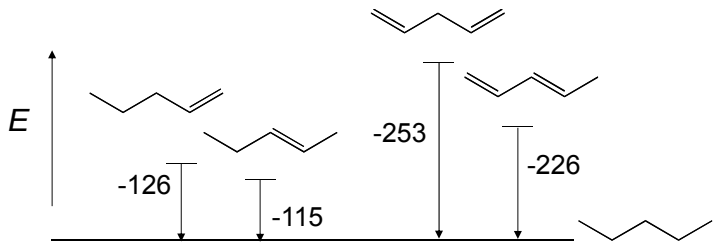
Ethene *1,3-Butadiene*



The Effect of Conjugation on the Stability of Dienes

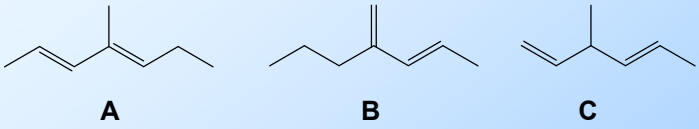
Heats of Hydrogenation





PRS

What is the correct order of stability of the following dienes (more stable > less stable)?



A **B** **C**

1 **A > B > C**

2 **B > A ≈ C**

3 **C > B > A**

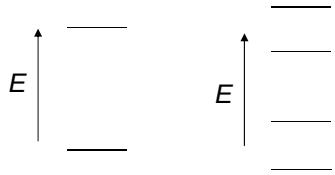
4 **A > C ≈ B**

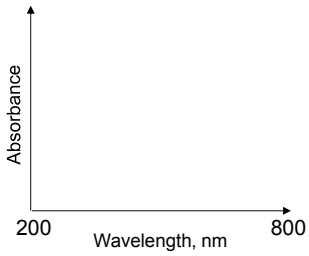
PRS

ULTRAVIOLET-VISIBLE SPECTROSCOPY

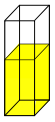
The energy required to promote electrons from π or n (non-bonding) orbitals to π^* corresponds to radiation in the ultraviolet-visible region of the electromagnetic spectrum (200-800 nm)

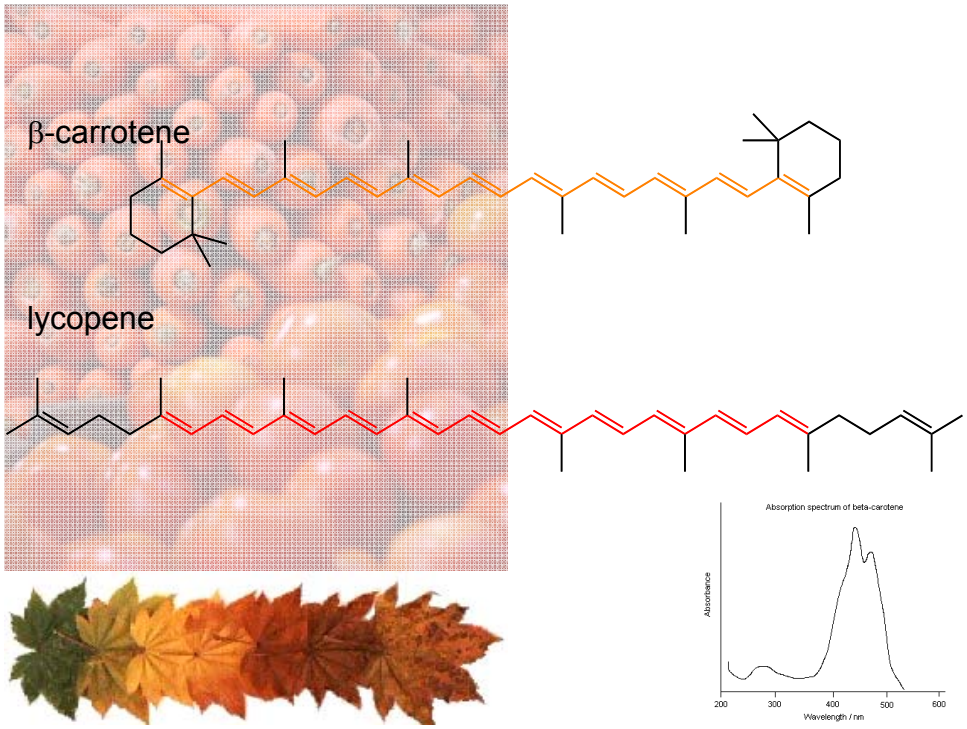
ethene *1,3-butadiene*

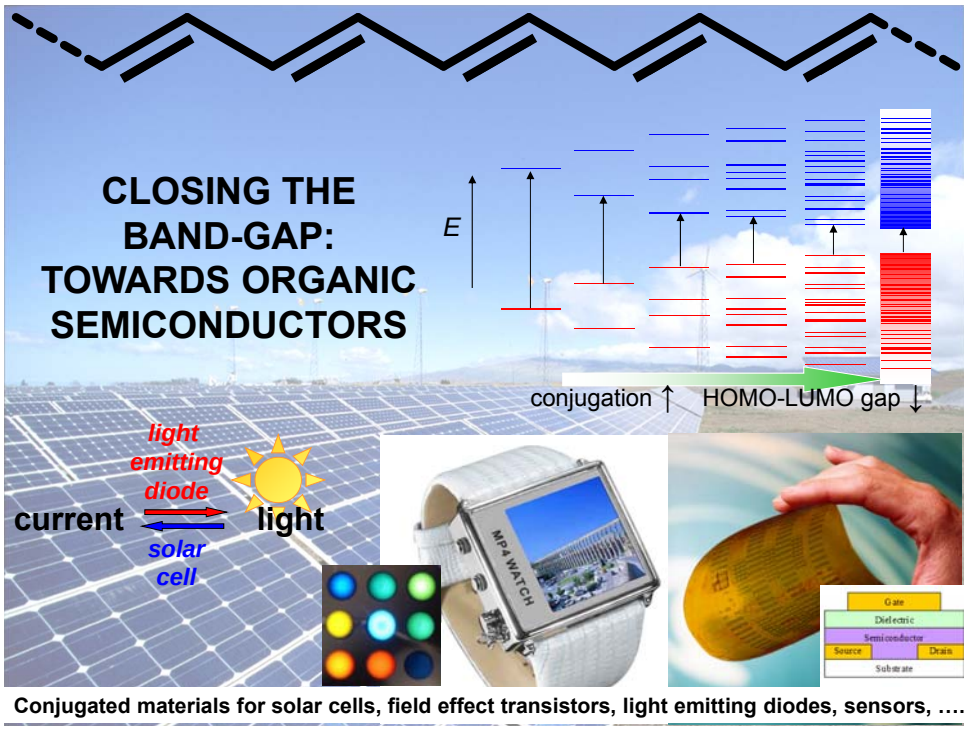


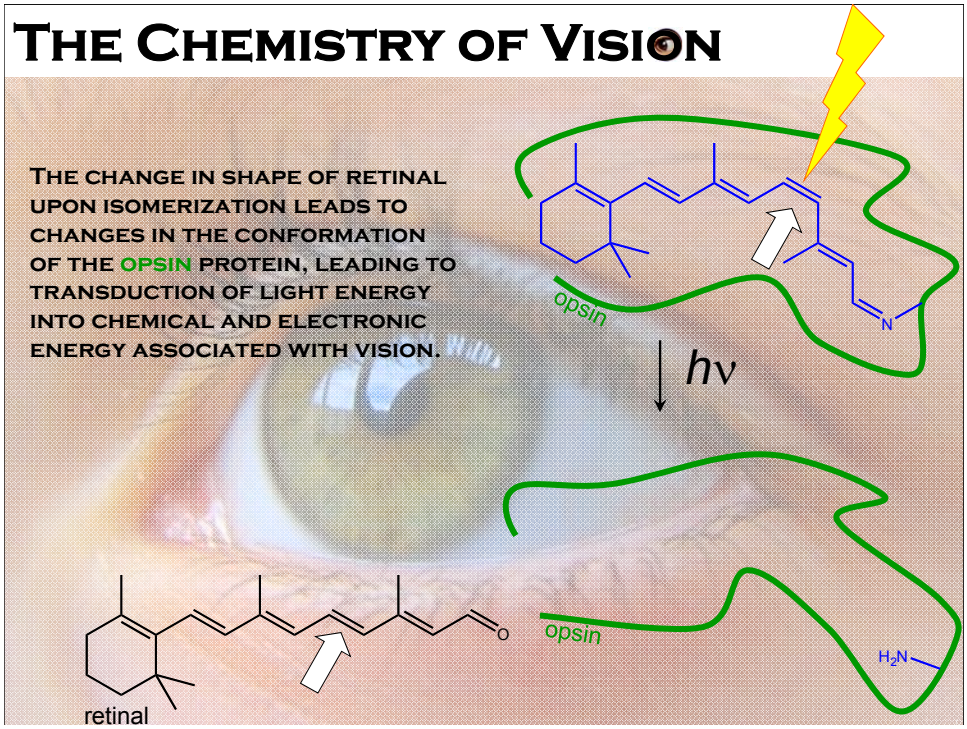


$$A = \varepsilon \, l \, c$$



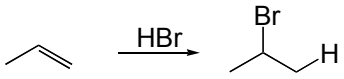

β-carrotene
lycopene
Absorption spectrum of beta-carotene
Absorbance
200
300
400
500
600
Wavelength / nm

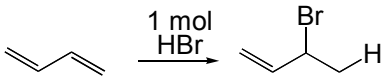

CLOSING THE BAND-GAP: TOWARDS ORGANIC SEMICONDUCTORS
E
conjugation ↑ HOMO-LUMO gap ↓
light emitting diode
current
light
solar cell
MP4 WATCH
Gate
Dielectric
Semiconductor
Source
Drain
Substrate
Conjugated materials for solar cells, field effect transistors, light emitting diodes, sensors, ….

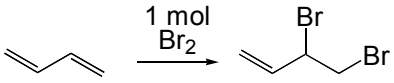


ELECTROPHILIC ADDITION TO CONJUGATED DIENES

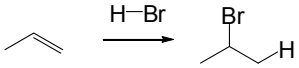
1,2- and 1,4- Addition

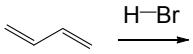


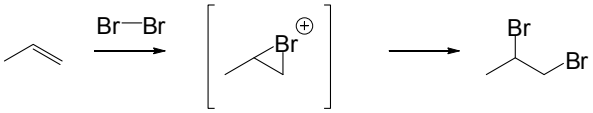


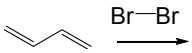


Mechanism



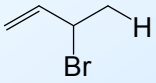




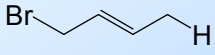


PRS

Which of the following is more stable?

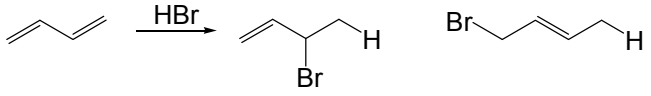


1



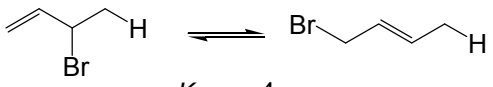
2

Kinetics versus Thermodynamics

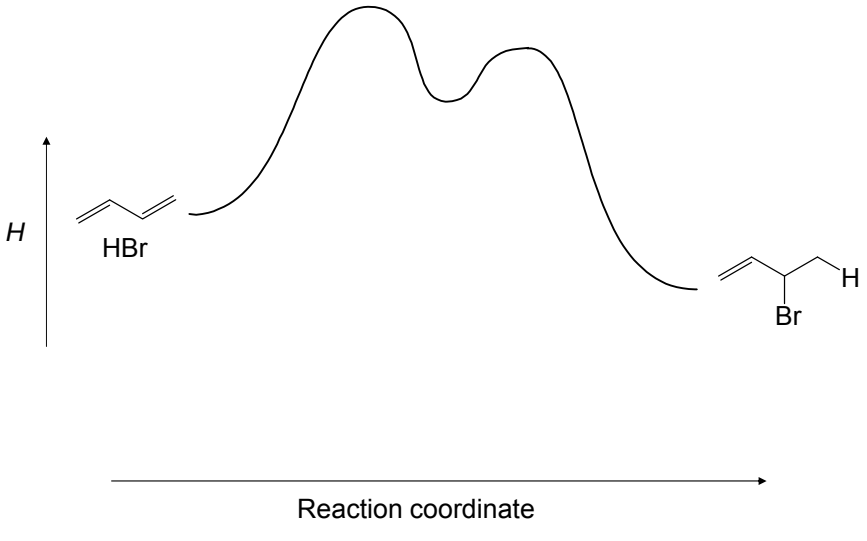


40 °C:	20%	80%
-15 °C:	54%	46%
-80 °C:	80%	20%

At 40 °C:

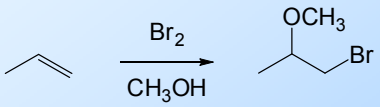


$K_{eqm} = 4$

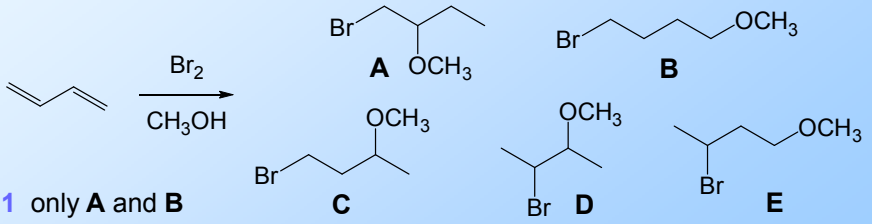


PRS

Propene reacts with Br_2 in CH_3OH to give 1-bromo-2-methoxypropane



Which of the following products are formed upon reaction of 1,3-butadiene with Br_2 in CH_3OH?



1 only **A** and **B**

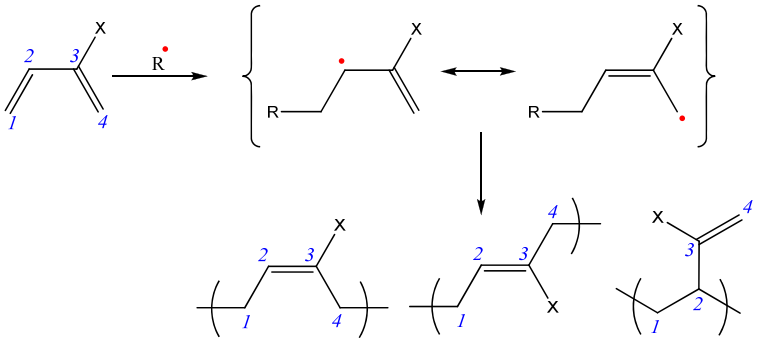
2 only **A**, **B** and **C**

3 only **D** and **E**

4 **A** , **B**, **C**, **D** and **E**

PRS

Natural rubber (X=CH_3) and Neoprene (X=Cl)

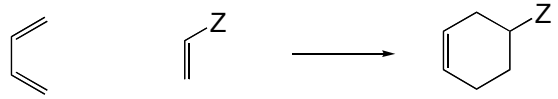


? *Prob:*13.20,23 ?

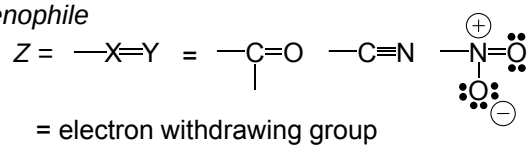
THE DIELS-ALDER REACTION: A 1,4-CYCLOADDITION REACTION OF DIENES

1,3-Dienes Undergo Addition Reactions with Electron-poor Alkenes

Mechanism

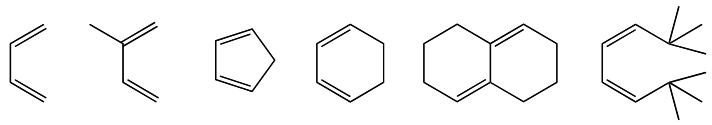


Dienophile



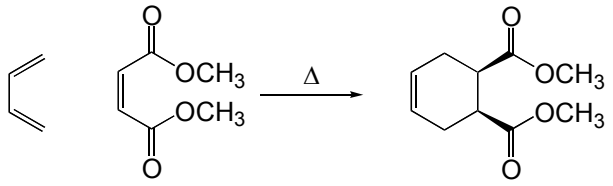
= electron withdrawing group

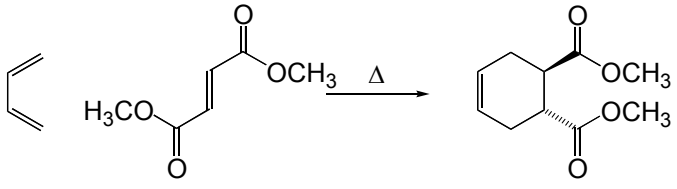
Diene – must be able to adopt an s-cis conformation



Product ("adduct")

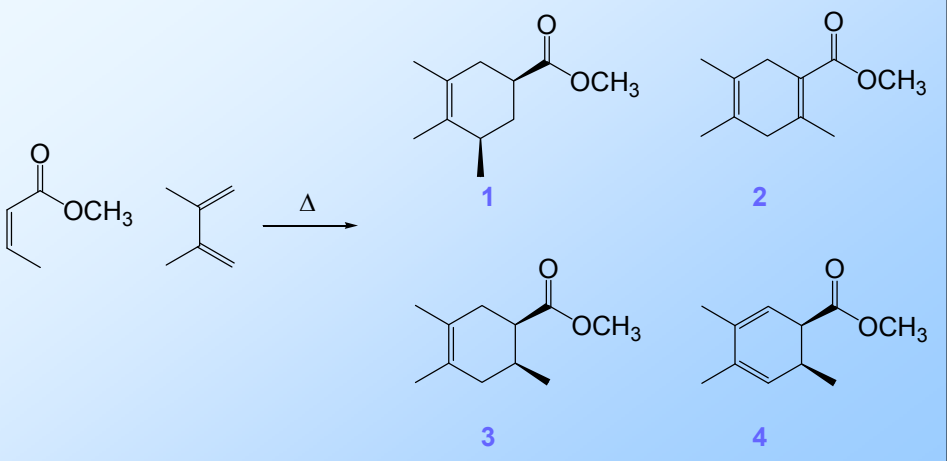
The Reaction is Stereospecific





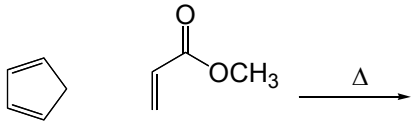
PRS

What is the major product of the following reaction?



PRS

Addition to Cyclic Dienes Gives Bicyclic Products….

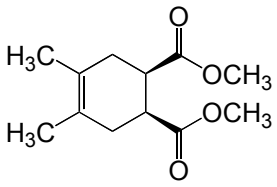


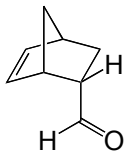
…with predominanty *endo* stereochemistry

DESIGNING MULTISTEP SYNTHESIS

Diels-Alder reactions always provide a six-membered ring containing a pi-bond. To determine which diene and dienophile can be used to make a Diels-Alder aduct, push electrons around to account for a retro-Diels-Alder process.

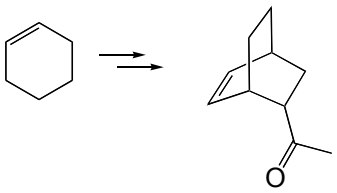
Problem [Solomons 13.24b,f] – Which diene and dienophile are required to prepare the following compounds?





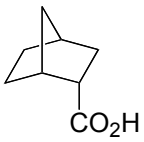
?

Problem - Provide a synthetic route to achieve the following transformation



?

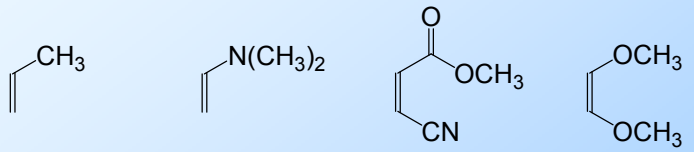
Problem - Provide a synthetic route to make the following molecule from starting materials with ≤5 carbon atoms.



?

PRS

Which of the following is the best dienophile in Diels-Alder reactions?



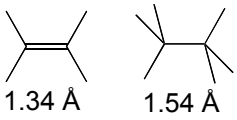
1 **2** **3** **4**

? *Prob:*13.16,18,19,24,25,28,40 ?

IT'S "*BENZENE*!": NOT CYCLOHEXATRIENE

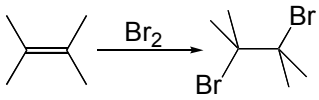
Benzene possesses different properties than alkenes

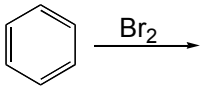
Structure

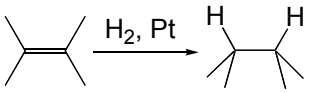


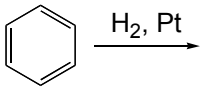
All carbon-carbon bonds: 1.42 Å

Reactivity

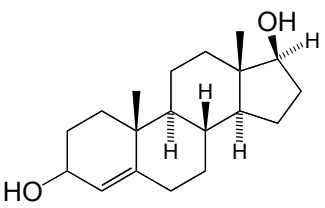




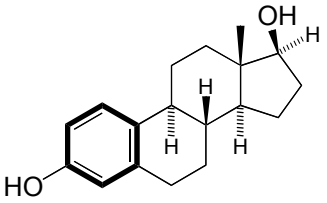




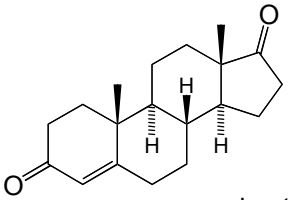
Sex



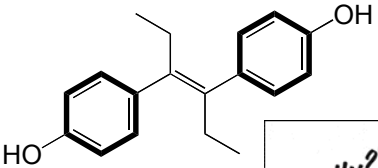
testosterone



estradiol

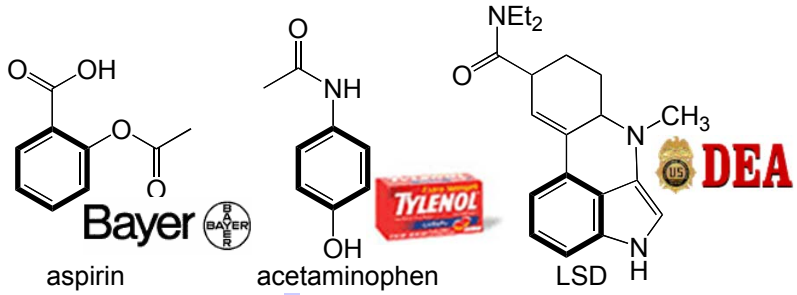


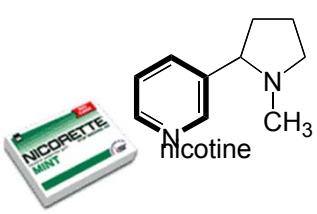
androstenedione

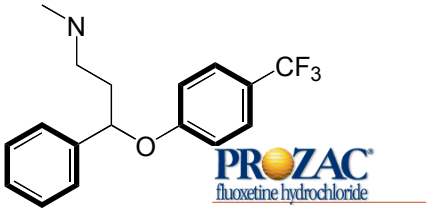


diethylstilbestrol (DES)

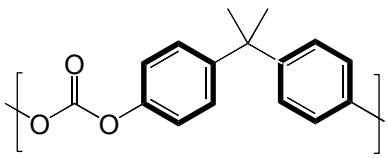
Drugs

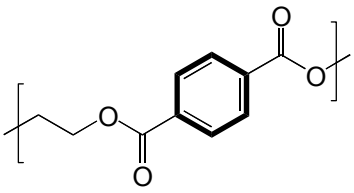






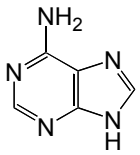
Rock and Roll, Disco too!



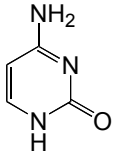


Aromatic Structures in Biology: DNA Bases

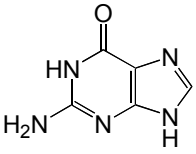
Adenine



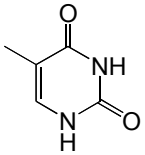
Cytosine

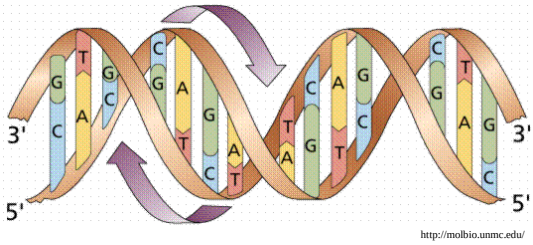


Guanine

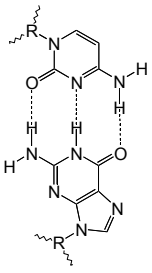


Tyrosine

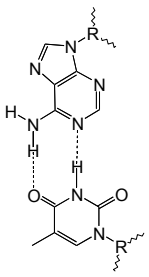




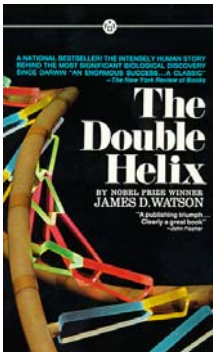
http://molbio.unmc.edu/



C-G

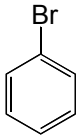


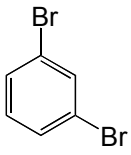
A-T

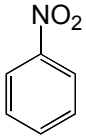


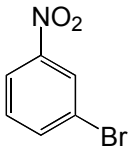
NOMENCLATURE OF BENZENE DERIVATIVES

Substituted Benzene Nomenclature

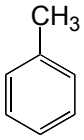




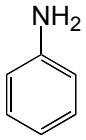




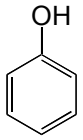
Trivial Base Names

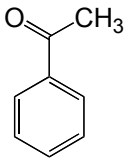


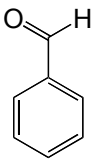
a common solvent



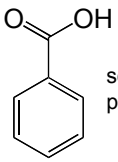
ingredient in dyes



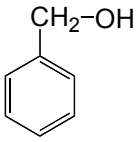


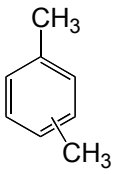


Almond flavor



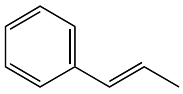
sodium salt: preservative

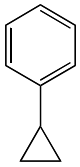




1,2-
1,3-
1,4-

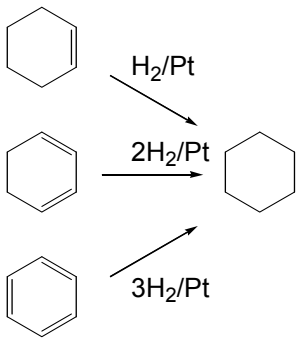
Phenyl Substituent Nomenclature





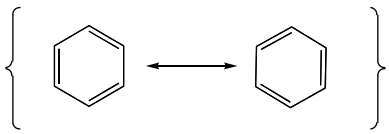
STABILITY OF BENZENE: EXPERIMENTAL OBSERVATIONS AND THEORY

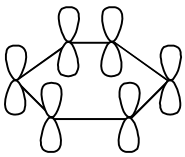
Heats of Hydrogenation as an Indication of Stability

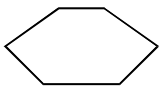


	ΔH (kJ/mol)	
	Predicted	Experimental
	-	-120
	-240	-232
	-360	-208

Resonance

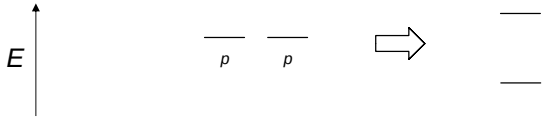




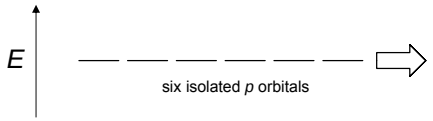


Combination of Atomic Orbitals

Alkenes:

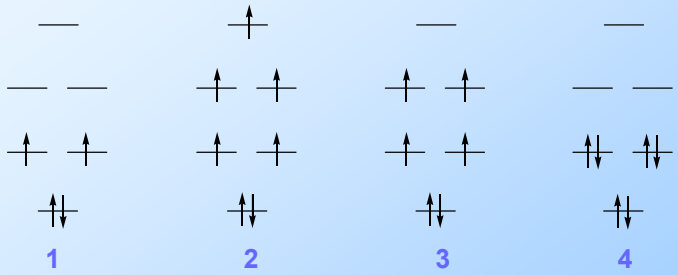


Benzene:



PRS

Considering the Pauli principle, aufbau principle and Hund's rule, what is the ground state electronic configuration of benzene?



HÜCKEL'S RULE, AROMATIC IONS AND HETEROARENES

cyclobutadiene

very reactive

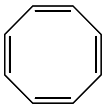
unstable

isolated only at very low temperatures

benzene

different reactivity from alkenes

especially stable



cyclooctatetraene

reacts like an alkene (i.e., addition reactions)

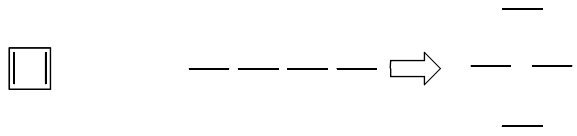
stable

Huckel's rule: Compounds with $(4n+2)$ π electrons (n=0,1,2…) in a planar cycle of p-orbitals are particularly stable ("aromatic").

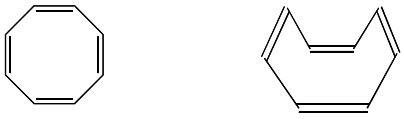
Compounds with $(4n)$ electrons in a planar cycle of p-orbitals are particularly unstable ("anti-aromatic").

Other compounds are non-aromatic

Why is Cyclobutadiene Unstable? The Origin of Anti-Aromaticity

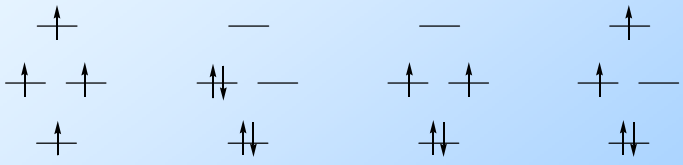


Cyclooctatetraene has 8 π Electrons: Why is it Stable (*i.e.*, not antiaromatic)?



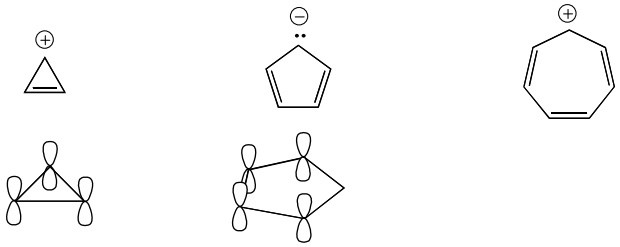
PRS

Considering the Pauli principle, aufbau principle and Hund's rule, what is the ground state electronic configuration of cyclobutadiene?



1 2 3 4

Aromatic and Antiaromatic Ions

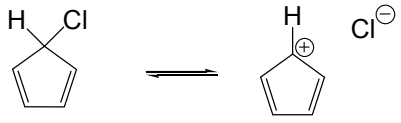


Consequences of Aromaticity on the Course of Reactions

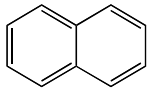
1,3-Cyclopentadiene has a low pK_a relative to other hydrocarbons

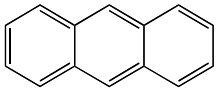
pK_a=16 pK_a=16

5-Chloro-1,3-cyclopentadiene does not undergo dissociation to form a resonance stabilized carbocation

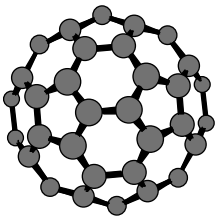


Fused Benzenes



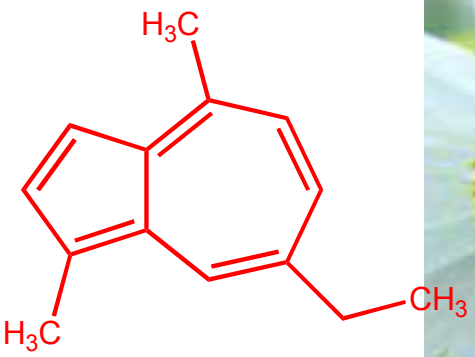


Buckminsterfullerene



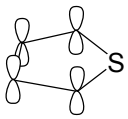
Chamazulene, 1,4-dimethyl-7-ethylazulene, extracted from chamomile flowers, is an anti-inflammatory.

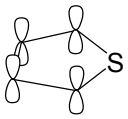
Chamazulene contains the C10 bicyclic azulene ring system. With **4n+2 electrons in an uninterrupted planar cycle of p-ortibals** it is an *aromatic* molecule.



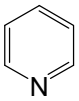
Heteroarenes

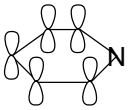
thiophene



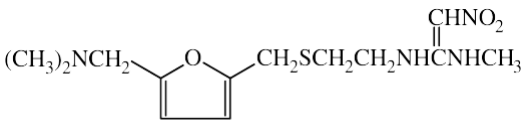


pyridine



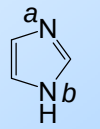


GlaxoSmithKline



PRS

Imidizole is an *aromatic* heterocycle found in biological systems. Each nitrogen has a lone pair of electrons. What type of orbital contains the lone pairs of electrons on each nitrogen?



imidazole

1 $a = p$; $b = sp^2$

2 $a = sp$; $b = sp^2$

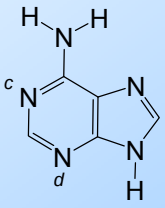
3 $a = sp^2$; $b = sp^2$

4 $a = sp^2$; $b = sp^3$

5 $a = sp^2$; $b = p$

PRS

Adenine is an *aromatic* heterocycle found in DNA. Each nitrogen has a lone pair of electrons. What type of orbital contains the lone pairs of electrons on each nitrogen?



adenine

1 $a = p$; $b = sp^2$

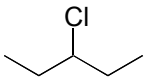
2 $a = sp$; $b = sp^2$

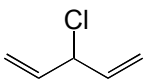
3 $a = sp^2$; $b = sp^2$

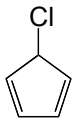
4 $a = sp^2$; $b = sp^3$

5 $a = sp^2$; $b = p$

Problem [Solomons 4.22] – Why does 3-chloro-1,4-pentadiene undergo hydrolysis (S_N1 reaction with H_2O) much more rapidly than 3-chloropentane? Why does 5-Chloro-1,3-cyclopentadiene undergo hydrolysis much more slowly?







? *Prob:* 14.16,17,21 ?

L

REVIEW: CONCEPTS

Resonance

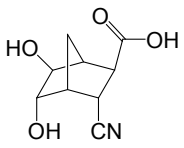
1,2- versus 1,4- electrophilic additions to conjugated dienes
(e.g., +Br_2, +H_2O/H^+, +Br_2,H_2O)

Diels-Alder cycloadditions

Aromaticity

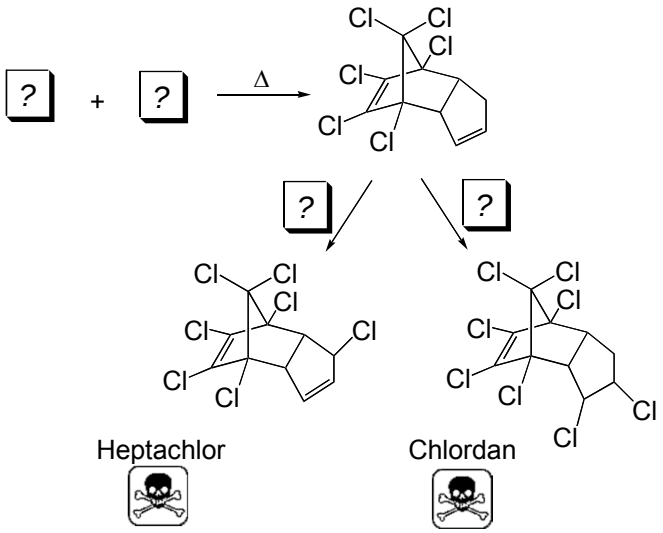
REVIEW: PROBLEMS

Problem. The following compound was prepared by a graduate student, Sahar Javanmard, as a potential therapeutic agent for treatment of drug abuse. How would you prepare this compound?

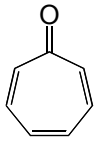


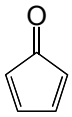
?

Problem [Solomons 13.31] – What are the substrates and reagents in the following scheme to prepare Heptchlor and Chlordan?

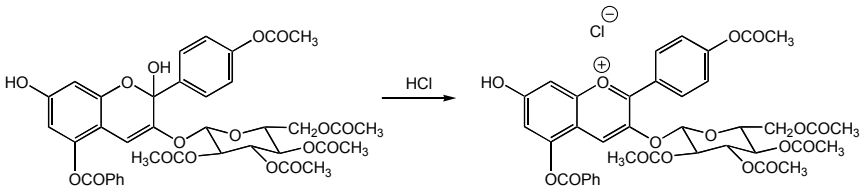


Problem [Solomons 14.21] - Cycloheptatrienone is very stable, whereas cyclopentadienone is unstable an undergoes Diel-Alder reaction with itself. Provide an explanation for these observations and provide the structure of the dimer of cyclopentadienone



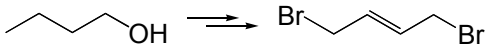


Problem [Solomons Learning Group Problem 14.1] – Callistephin chloride is a red pigment found in the purple-red aster. The last step in its synthesis is shown below. What kind of process is taking place? What is the mechanism? Why is this a reasonable mechanism?

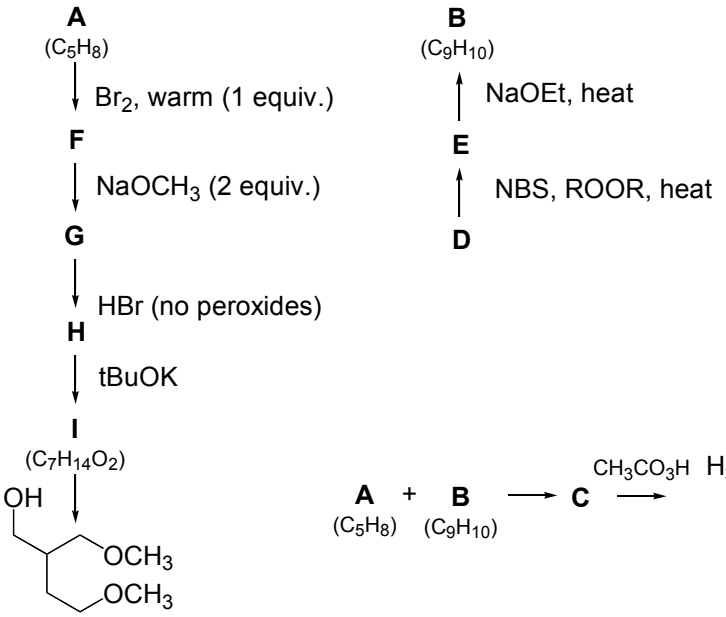


Callistephin chloride

Problem [Solomons 13.19c] - How would you convert 1-butanol into 1,4-dibromo-2-butene?



Problem [Solomons Group Learning Problem 13.1] - What are the structures of **A**-**I**?



TOPICS ON EXAM

Types of Questions

- Predict the product of individual reactions (know the reagents!)
- Write a detailed mechanism for reactions (understand nucleophiles, electrophiles and radicals!)
- Provide IUPAC names for compounds (including common names for substituted benzenes; review rules from CHEM 2311)
- Assess stability of reactive intermediates and compounds (*i.e.*, resonance, aromatic versus anti-aromatic, Hückel's rule)

-Do other problems in the book - they are great examples of the types of problems on the exam!

Preparing for Exam 1

- Get up-to-date *NOW!*
- Work as many problems as possible. Do the problems first, then consult the solutions manual
- Work in groups, discuss chemistry, teach and test each other
- Do the "Learning Group Problem" at the end of the chapter