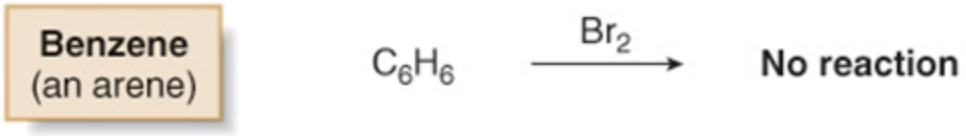
Benzene and Aromatic Compounds

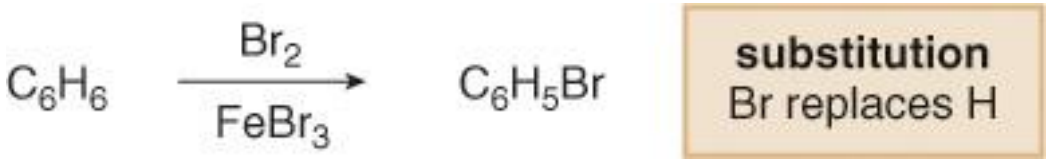
Chapter 15
Organic Chemistry, *8th Edition*
John McMurry

Background

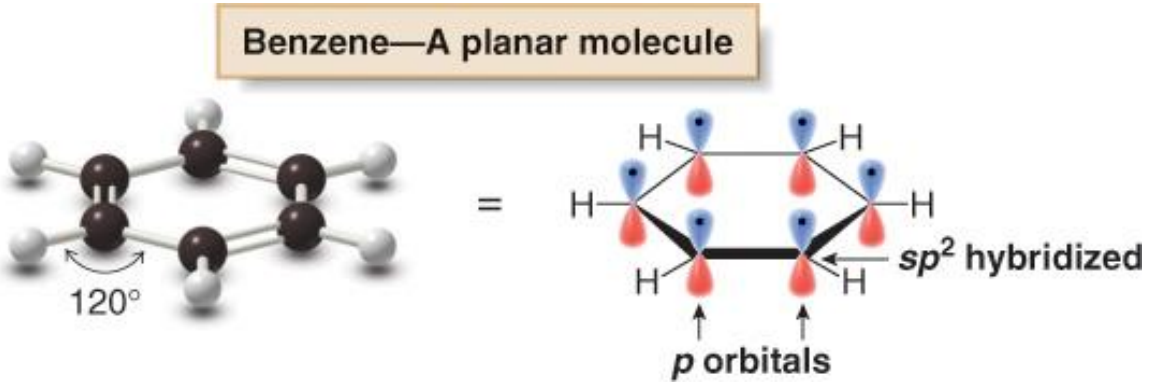
- Benzene (C_6H_6) is the simplest aromatic hydrocarbon (or arene).
- Four degrees of unsaturation.
- It is planar.
- All C—C bond lengths are equal.
- Whereas unsaturated hydrocarbons such as alkenes, alkynes and dienes readily undergo addition reactions, benzene does not.

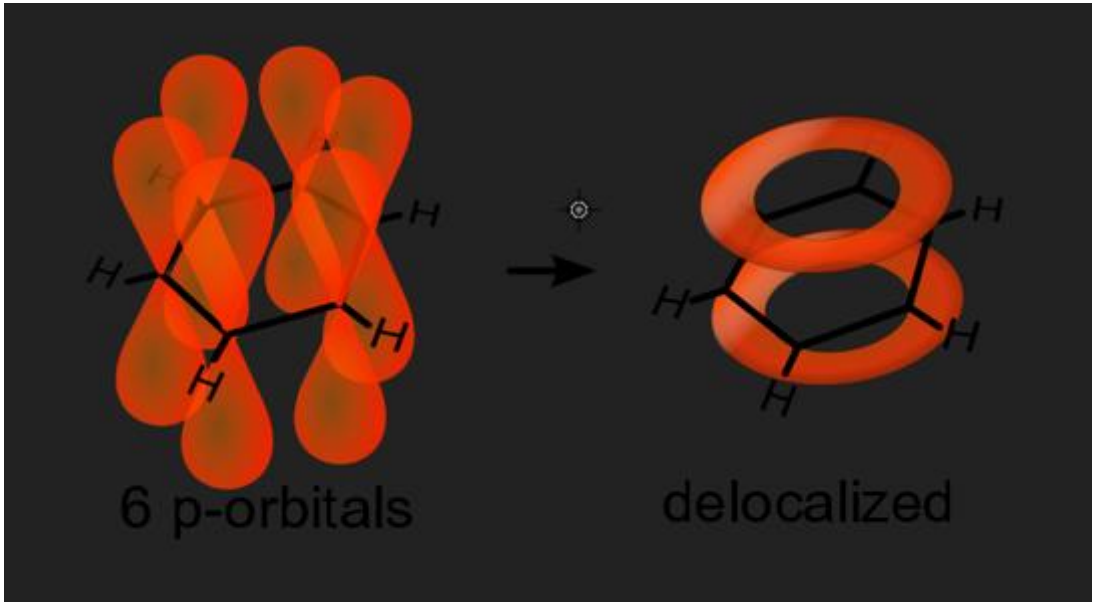


- Benzene reacts with bromine only in the presence of $FeBr_3$ (a Lewis acid), and the reaction is a substitution, not an addition.



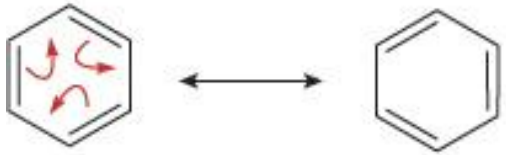
The Structure of Benzene: MO





The Structure of Benzene: Resonance

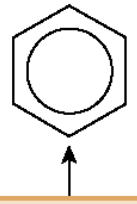
The true structure of benzene is a resonance hybrid of the two Lewis structures.



The hybrid

The electrons in the π bonds are **delocalized** around the ring.

Some texts draw benzene as a hexagon with an inner circle:



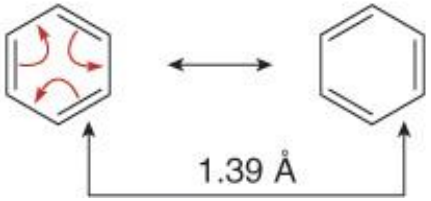
The circle represents the **six π electrons,** distributed over the six atoms of the ring.

CH_3-CH_3

1.53 Å

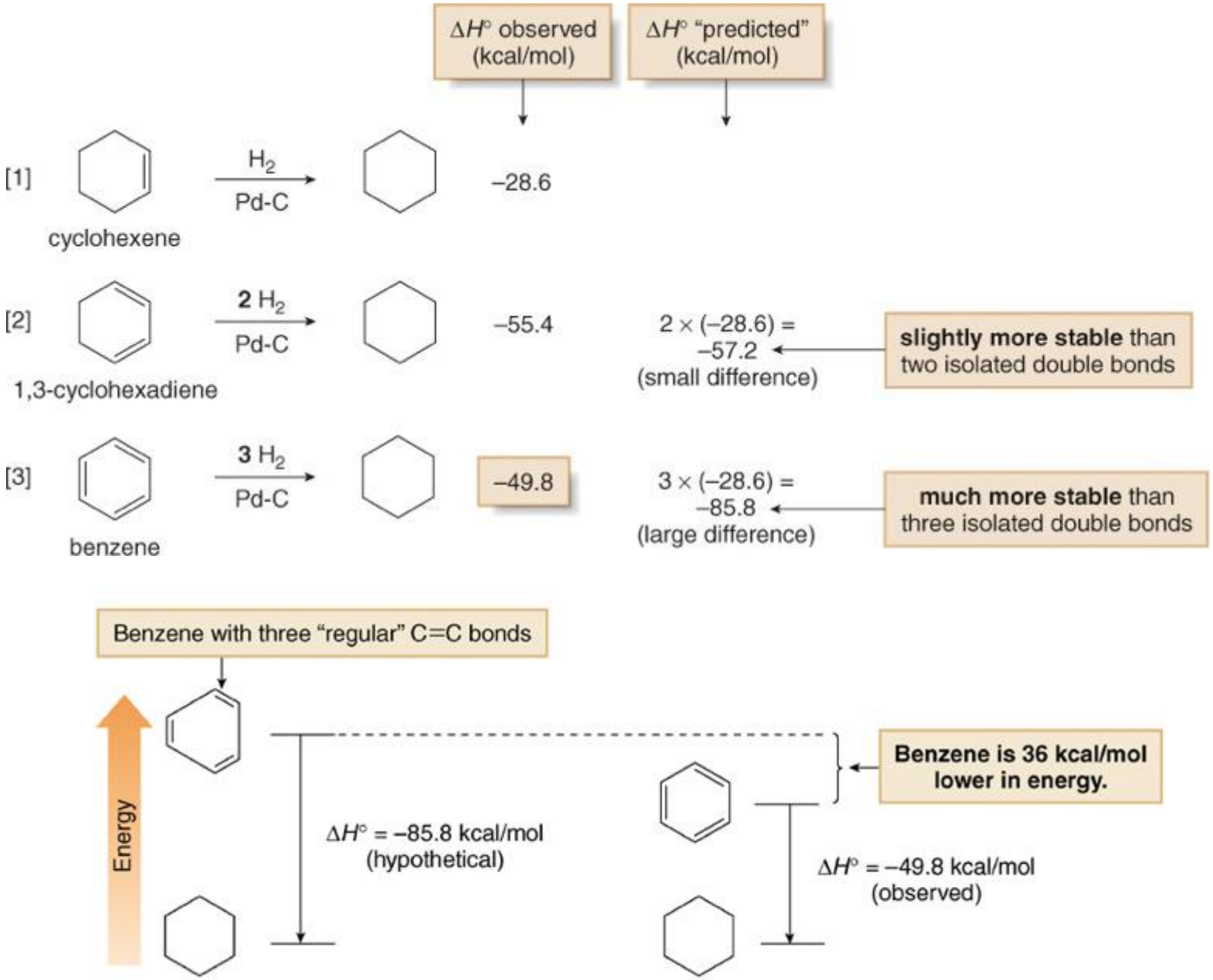
$CH_2=CH_2$

1.34 Å



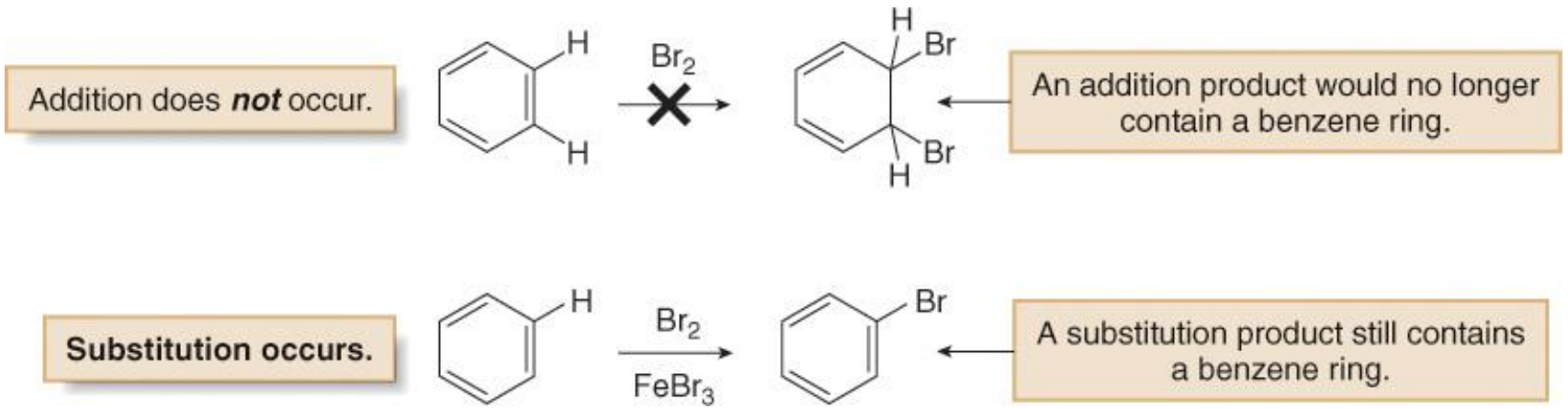
The C–C bonds in benzene are equal and intermediate in length.

Aromaticity – Resonance Energy



Stability of Benzene - Aromaticity

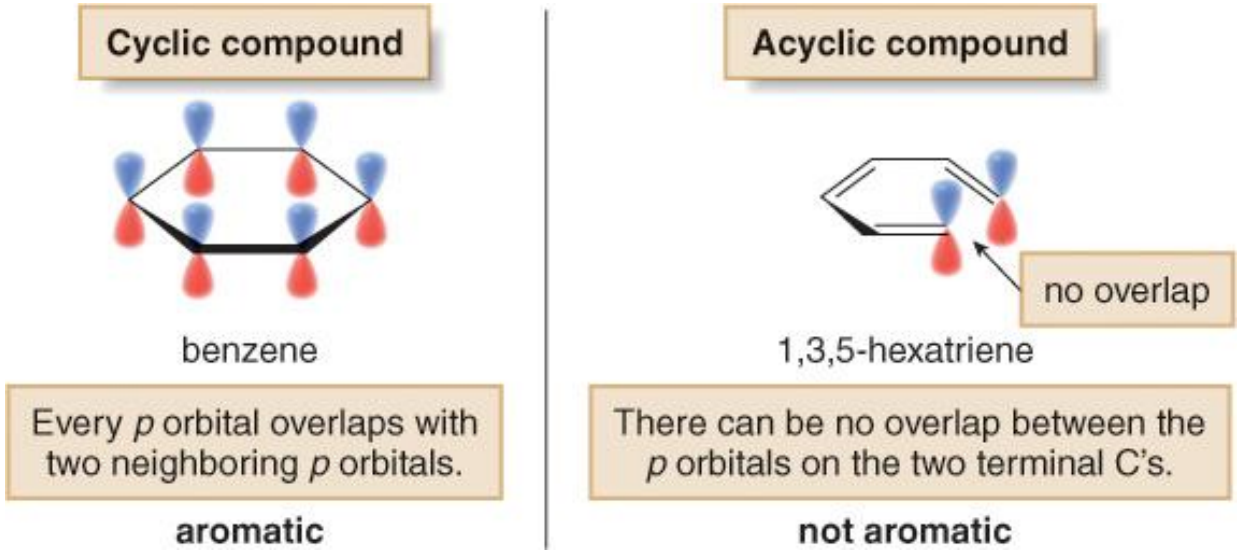
Benzene does not undergo addition reactions typical of other highly unsaturated compounds, including conjugated dienes.



The Criteria for Aromaticity

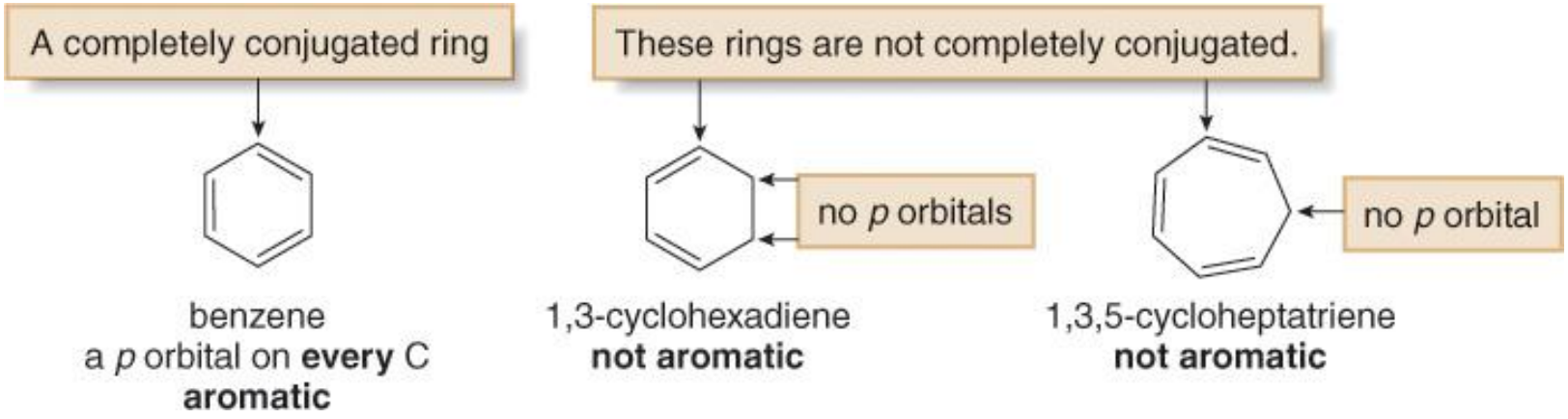
Four structural criteria must be satisfied for a compound to be aromatic.

[1] A molecule must be cyclic.



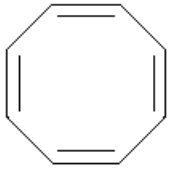
The Criteria for Aromaticity

[2] A molecule must be completely conjugated (all atoms sp^2).

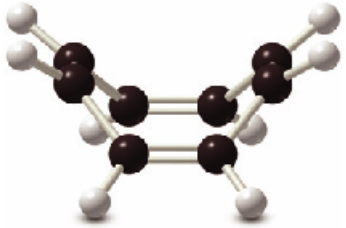


The Criteria for Aromaticity

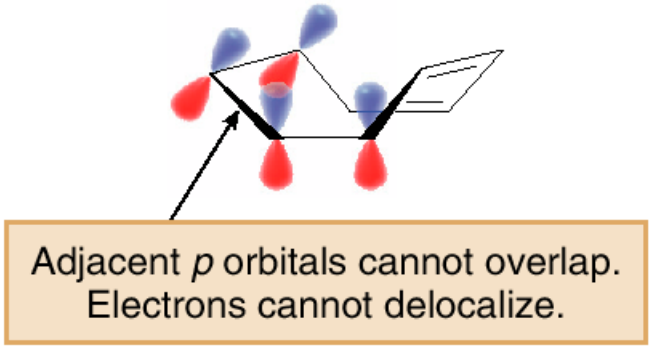
[3] A molecule must be planar.



cyclooctatetraene
not aromatic



a tub-shaped,
eight-membered ring



The Criteria for Aromaticity—Hückel's Rule

[4] A molecule must satisfy Hückel's rule.

- An aromatic compound must contain $4n + 2$ π electrons (n = 0, 1, 2, and so forth).
- Cyclic, planar, and completely conjugated compounds that contain $4n$ π electrons are especially unstable, and are said to be *antiaromatic.*

Benzene
An aromatic compound

$4n + 2 = 4(1) + 2 =$
6 π electrons
aromatic

Cyclobutadiene
An antiaromatic compound

$4n = 4(1) =$
4 π electrons
antiaromatic

Table 17.2 The Number of π Electrons That Satisfy Hückel's Rule

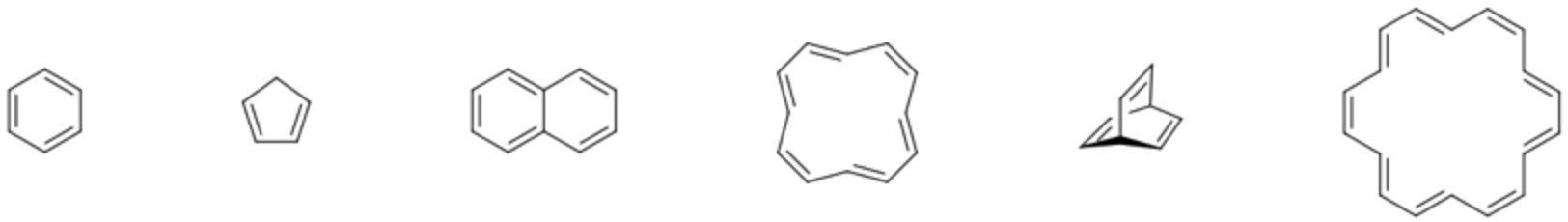
n	$4n + 2$
0	2
1	6
2	10
3	14
4, etc.	18

The Criteria for Aromaticity—Hückel's Rule

1. Aromatic—A cyclic, planar, completely conjugated compound with $4n + 2$ π electrons.

3. Antiaromatic—A cyclic, planar, completely conjugated compound with $4n$ π electrons.

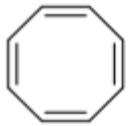
5. Not aromatic (nonaromatic)—A compound that lacks one (or more) of the following requirements for aromaticity: being cyclic, planar, and completely conjugated.



aromatic nonaromatic aromatic antiaromatic nonaromatic aromatic

Annulenes

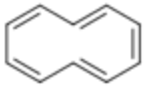
Cyclooctatetraene
8 π electrons



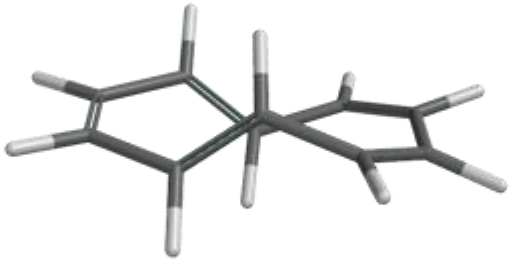
antiaromatic

nonaromatic

10-Annulene
10 π electrons



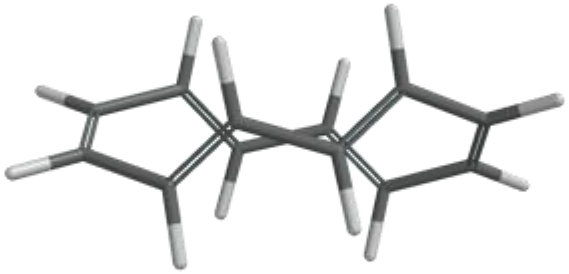
aromatic



nonaromatic

12-Annulene
12 π electrons

antiaromatic



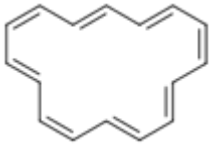
nonaromatic

Annulenes

14-Annulene
14 π electrons

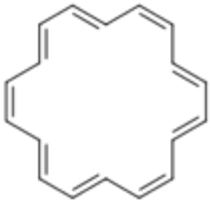
aromatic

16-Annulene
16 π electrons



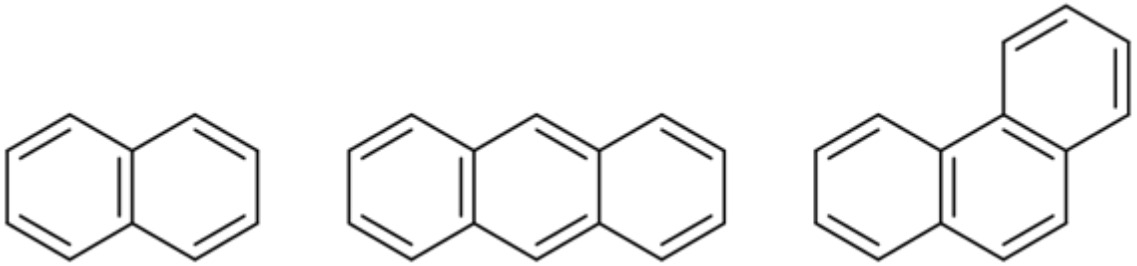
antiaromatic

18-Annulene
18 π electrons



aromatic

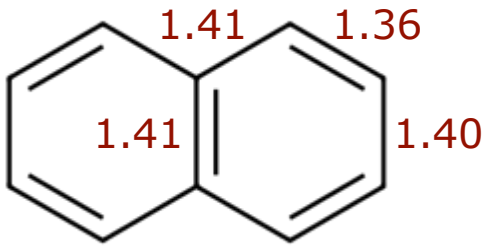
Polycyclic Aromatic Hydrocarbons (PAH)

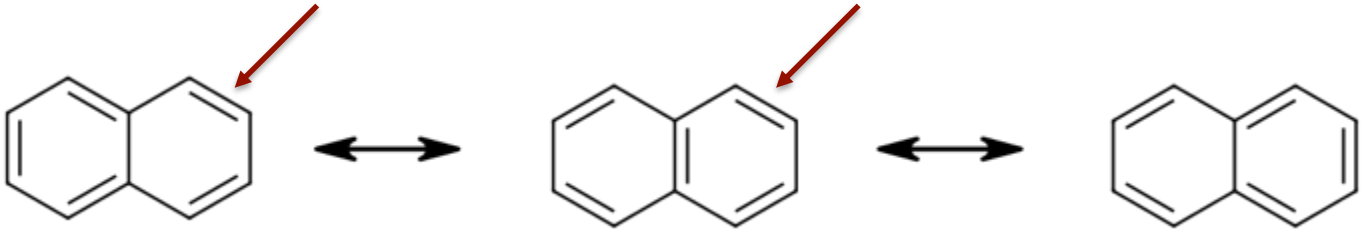


10 π | 14 π

	naphthalene	anthracene	phenanthrene
resonance energy	61	83	91
per ring	30.5	27.7	30.3

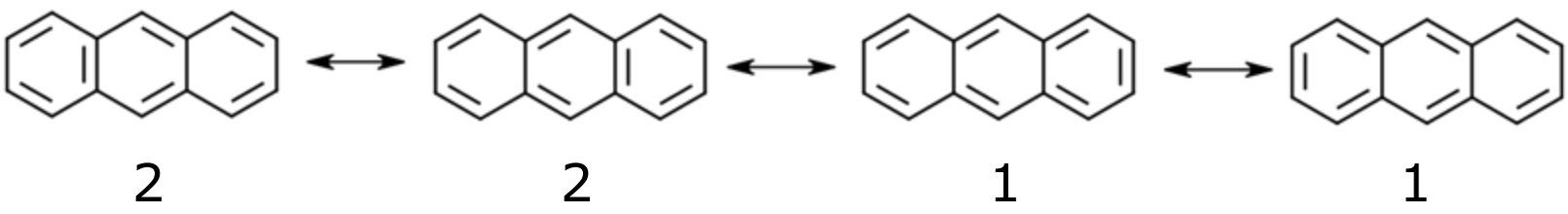
Polycyclic Aromatic Hydrocarbons (PAH)

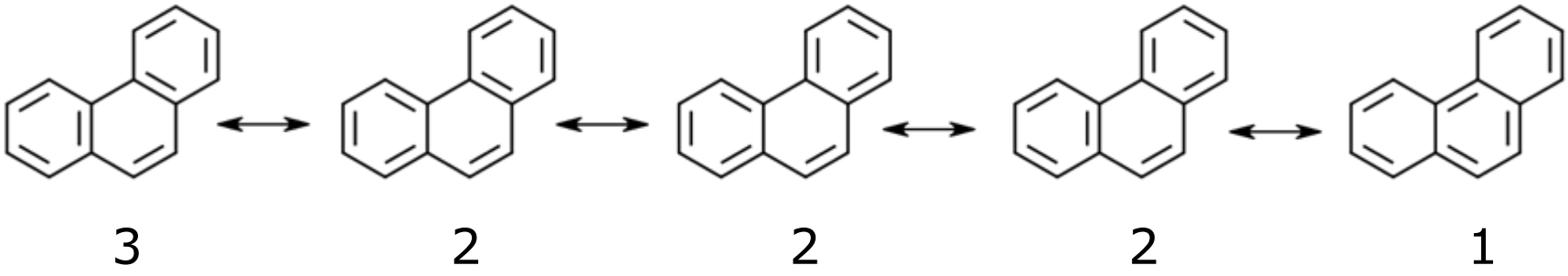




In 2 resonance structures there is a double bond between C1 and C2

Polycyclic Aromatic Hydrocarbons (PAH)

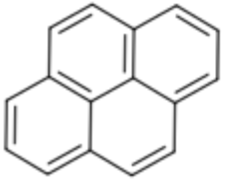




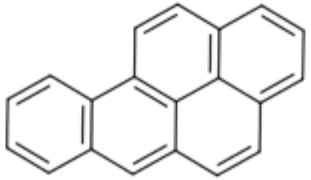
In phenanthrene there are more resonance structures containing 6-e

Polycyclic Aromatic Hydrocarbons (PAH)

the Hückel rule does not apply to large fused systems: the following are all aromatic

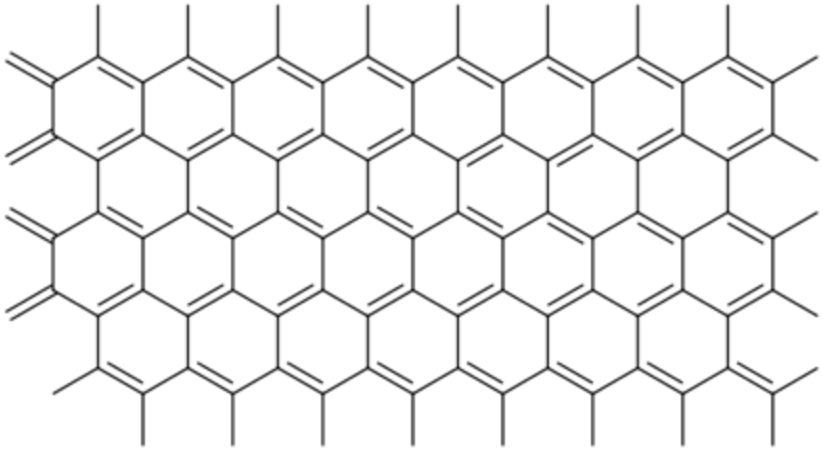


pyrene
16 π



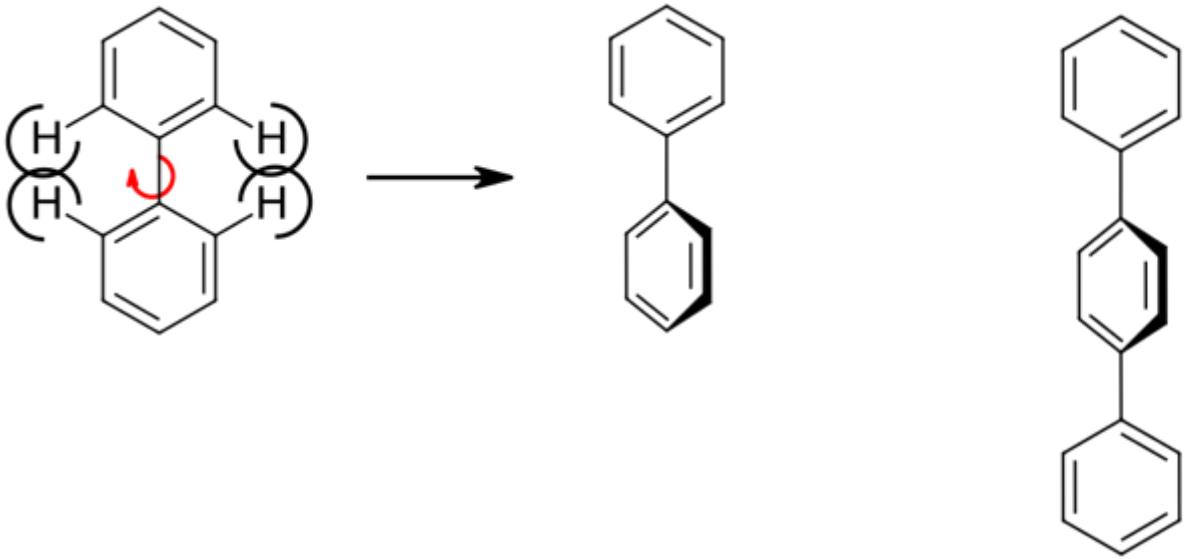
benzopyrene
20 π

coronene
24 π



graphene

Diphenyl and Terphenyl



- In diphenyl and terphenyl the rings are twisted around the central single bond to avoid torsional strain.
- The aromatic rings are independent.

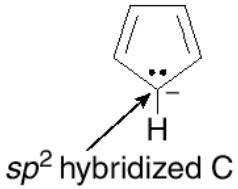
Other Aromatic Compounds

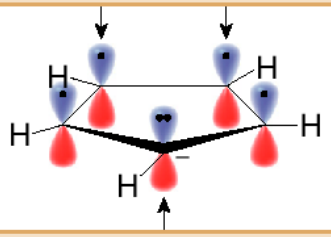
cyclopentadiene
not aromatic
$pK_a = 15$

cyclopentadienyl anion
aromatic
a stabilized conjugate base

The cyclopentadienyl anion

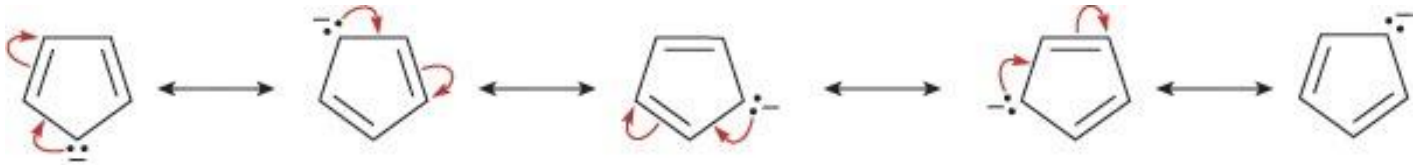
The ring is completely conjugated with **6 π electrons**.





The lone pair resides in a *p* orbital.

- **The cyclopentadienyl anion is aromatic because it is cyclic, planar, completely conjugated, and has six π electrons.**



Other Aromatic Compounds

cyclopentadienyl anion
- **6** π electrons
- contains $4n + 2$ π electrons

aromatic

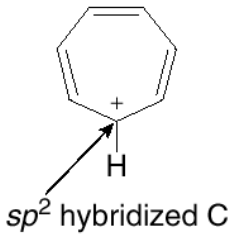
cyclopentadienyl cation
- **4** π electrons
- contains $4n$ π electrons

antiaromatic

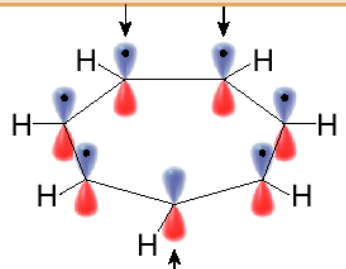
cyclopentadienyl radical
- **5** π electrons
- does not contain either $4n$ or $4n + 2$ π electrons

nonaromatic

The tropylium cation

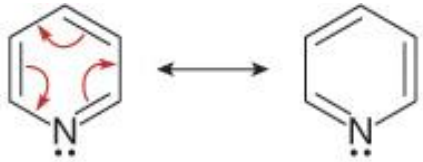


The ring is completely conjugated with **6 π electrons**.

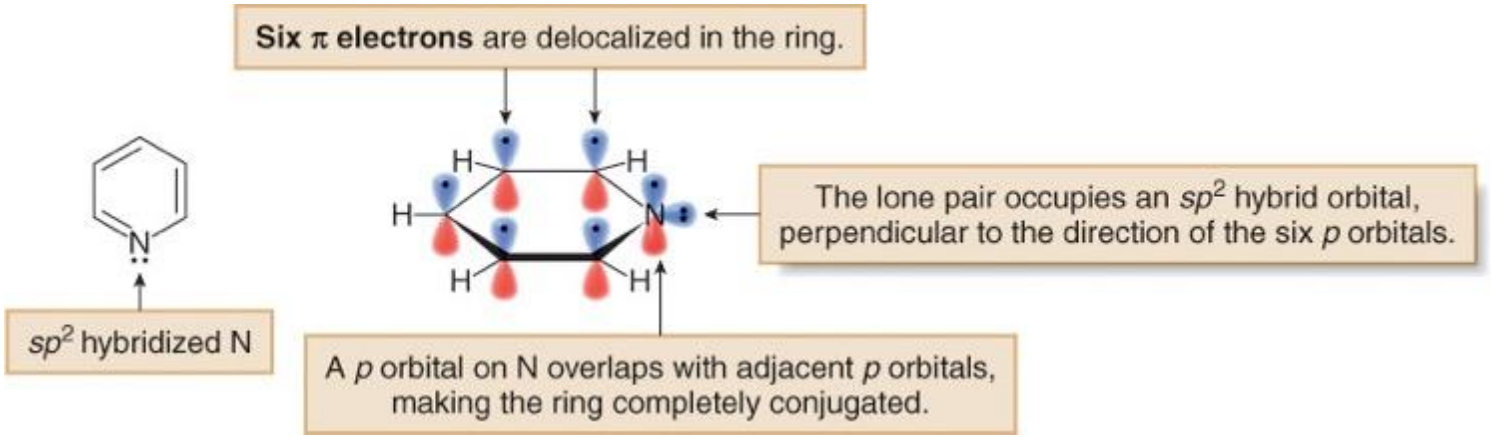


- The tropylium cation is aromatic because it is cyclic, planar, completely conjugated, and has six π electrons delocalized over the seven atoms of the ring.

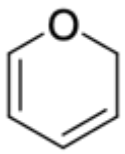
Aromatic Heterocycles: Pyridine



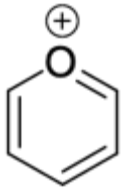
two resonance structures for pyridine
6 π electrons



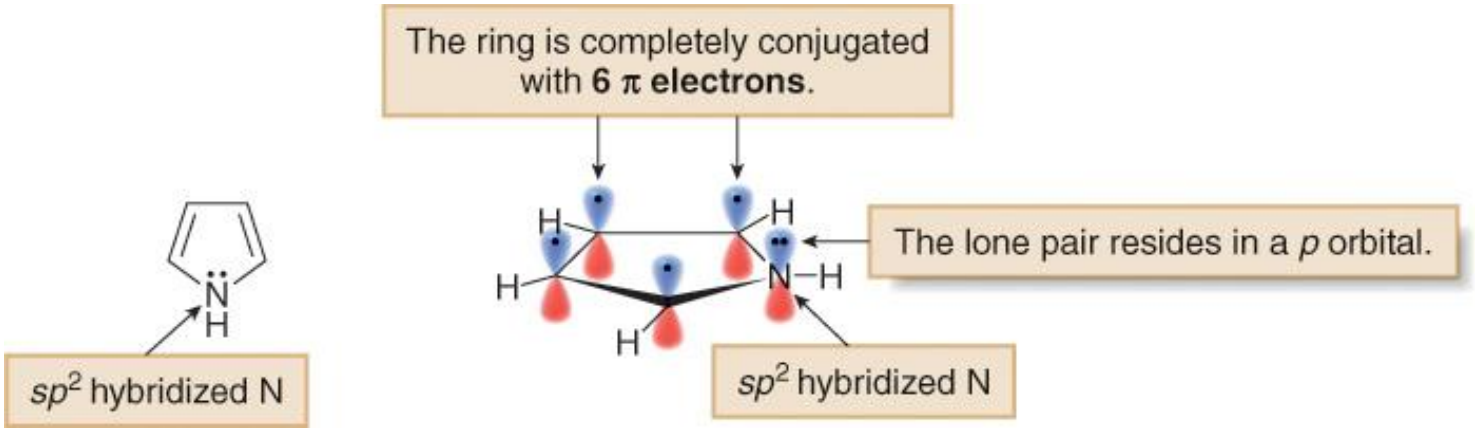
2H-pyran
4 π electrons
nonaromatic

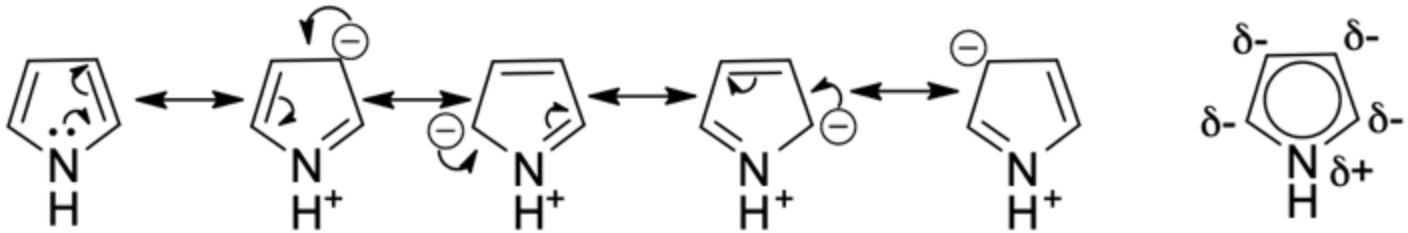


pyrilium ion
6 π electrons
aromatic



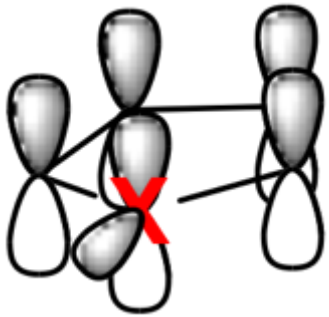
Aromatic Heterocycles: Pyrrole





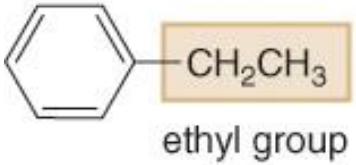
furan

thiophen



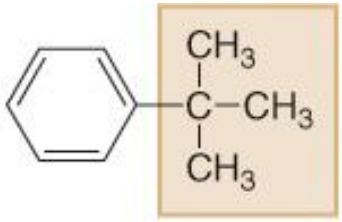
Nomenclature: 1 Substituent

Systematic:



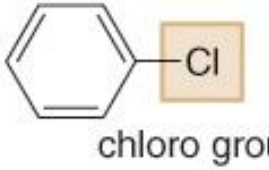
ethyl group

ethylbenzene



tert-butyl group

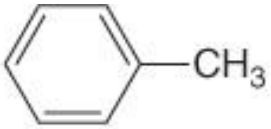
tert-butylbenzene



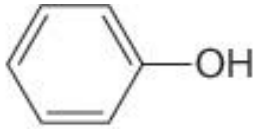
chloro group

chlorobenzene

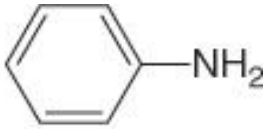
Common:



toluene
(methylbenzene)



phenol
(hydroxybenzene)

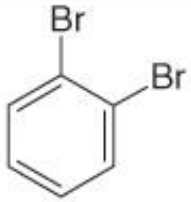


aniline
(aminobenzene)

Nomenclature: 2 Substituents

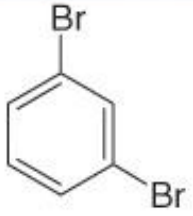
Identical:

1,2-disubstituted benzene
ortho isomer



1,2-dibromobenzene
o-dibromobenzene

1,3-disubstituted benzene
meta isomer



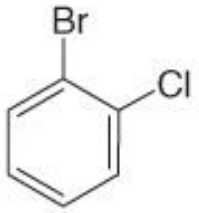
1,3-dibromobenzene
m-dibromobenzene

1,4-disubstituted benzene
para isomer

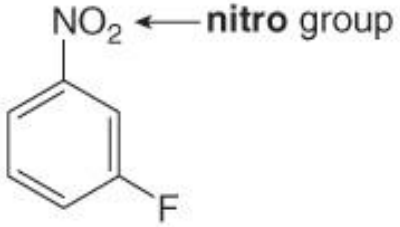
1,4-dibromobenzene
p-dibromobenzene

Different:

Alphabetize two different substituent names:

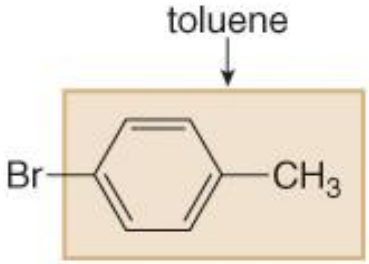


***o*-bromochloro-benzene**

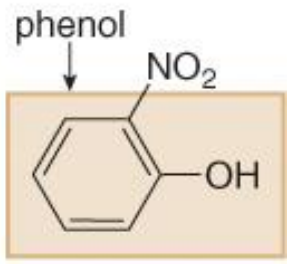


***m*-fluoronitro-benzene**

Use a common root name:



***p*-bromo**toluene**

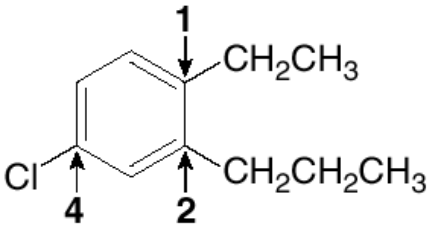


***o*-nitro**phenol**

Nomenclature: 3 or More Substituents

Examples of naming polysubstituted benzenes

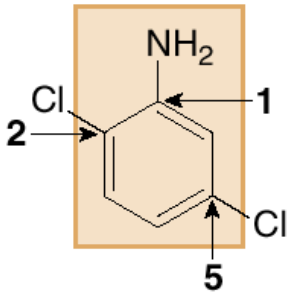
[1]



- Assign the lowest set of numbers.
- Alphabetize the names of all the substituents.

4-chloro-1-ethyl-2-propylbenzene

[2]

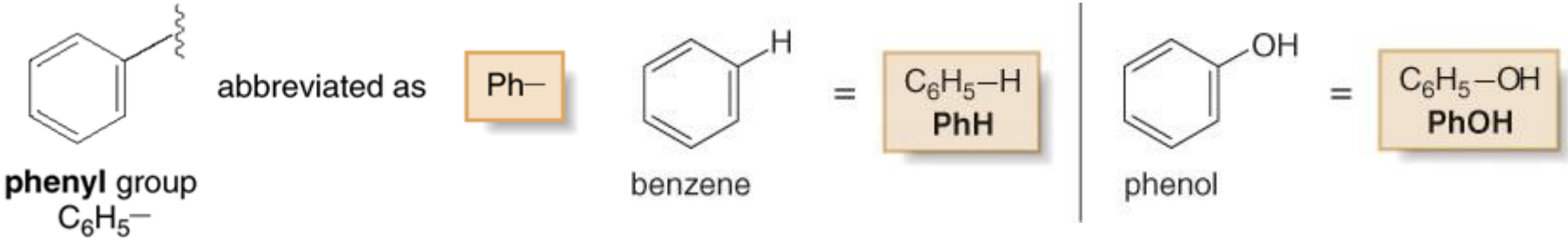


- Name the molecule as a derivative of the common root **aniline.**
- Designate the position of the NH_2 group as "1," and then assign the lowest possible set of numbers to the other substituents.

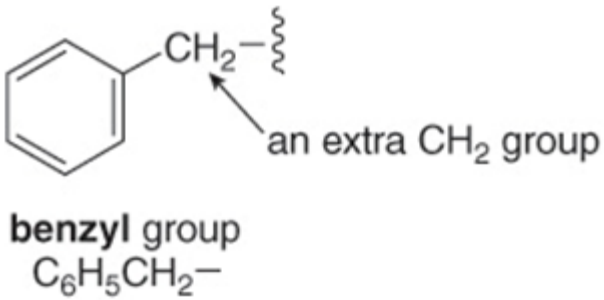
2,5-dichloroaniline

Nomenclature

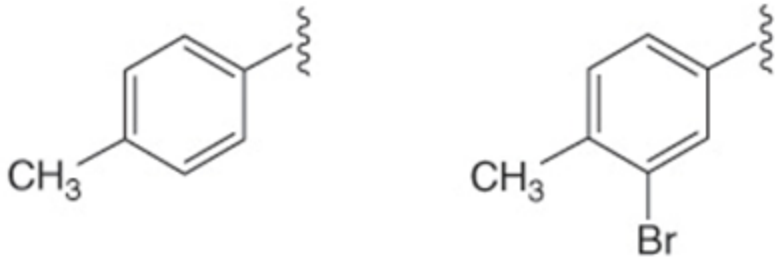
A benzene substituent is called a phenyl group, and it can be abbreviated in a structure as "Ph-".



The benzyl group:



Aryl groups:

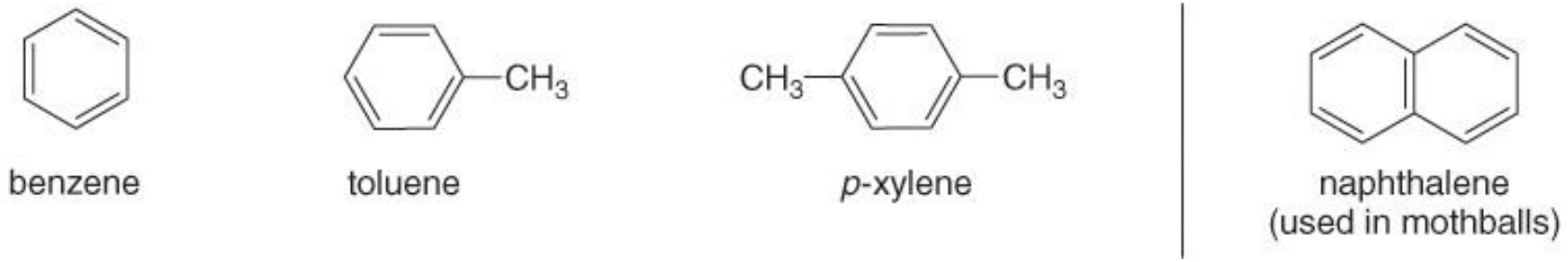


Interesting Aromatic Compounds

- Benzene and toluene, are obtained from petroleum refining and are useful starting materials for synthetic polymers.

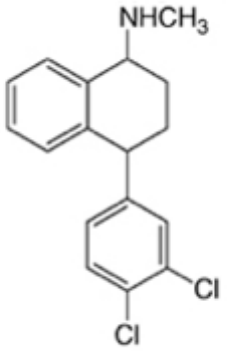
- Compounds containing two or more benzene rings that share carbon—carbon bonds are called polycyclic aromatic hydrocarbons (PAHs). Naphthalene, the simplest PAH, is the active ingredient in mothballs.

The components of the gasoline additive BTX

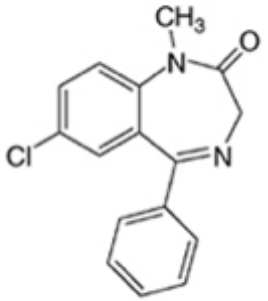


benzene | toluene | *p*-xylene | naphthalene (used in mothballs)

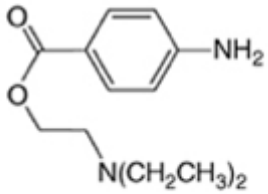
Interesting Aromatic Compounds



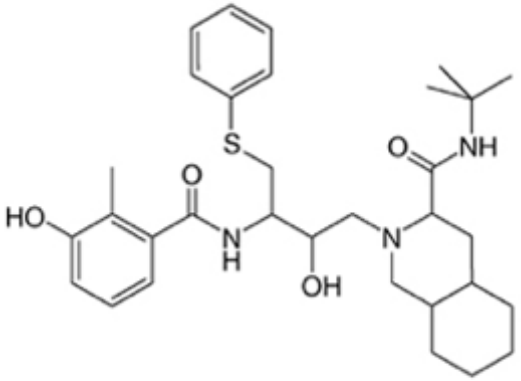
- Trade name: **Zoloft**
- Generic name: **sertraline**
- Use: a psychotherapeutic drug for depression and panic disorders



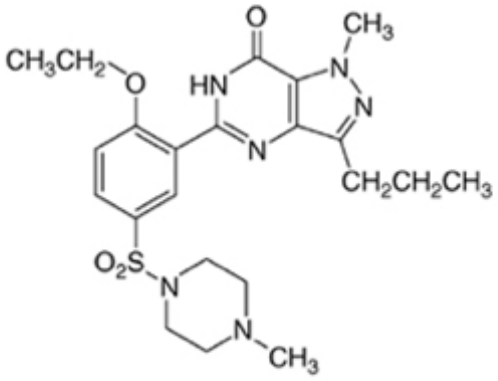
- Trade name: **Valium**
- Generic name: **diazepam**
- Use: a sedative



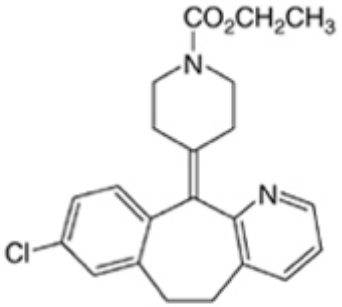
- Trade name: **Novocain**
- Generic name: **procaine**
- Use: a local anesthetic



- Trade name: **Viracept**
- Generic name: **nelfinavir**
- Use: an antiviral drug used to treat HIV



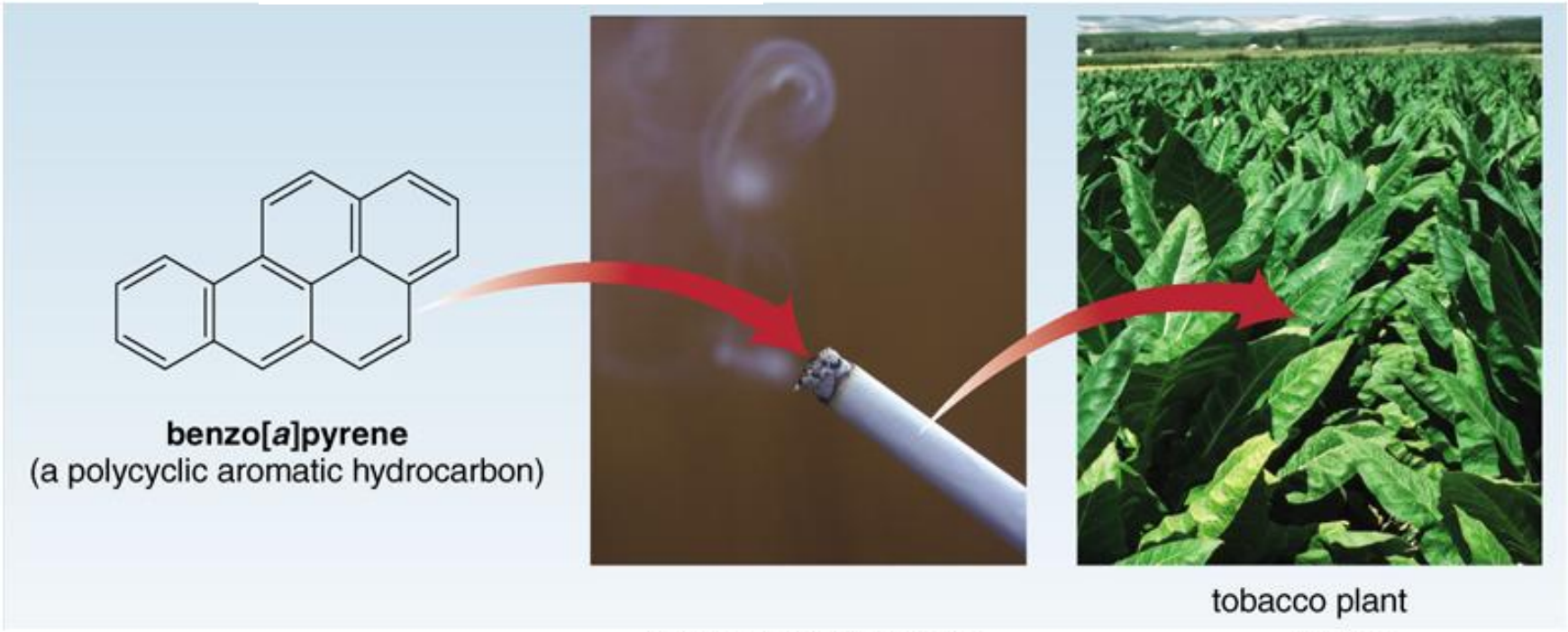
- Trade name: **Viagra**
- Generic name: **sildenafil**
- Use: a drug used to treat erectile dysfunction



- Trade name: **Claritin**
- Generic name: **loratadine**
- Use: an antihistamine for seasonal allergies

Interesting Aromatic Compounds

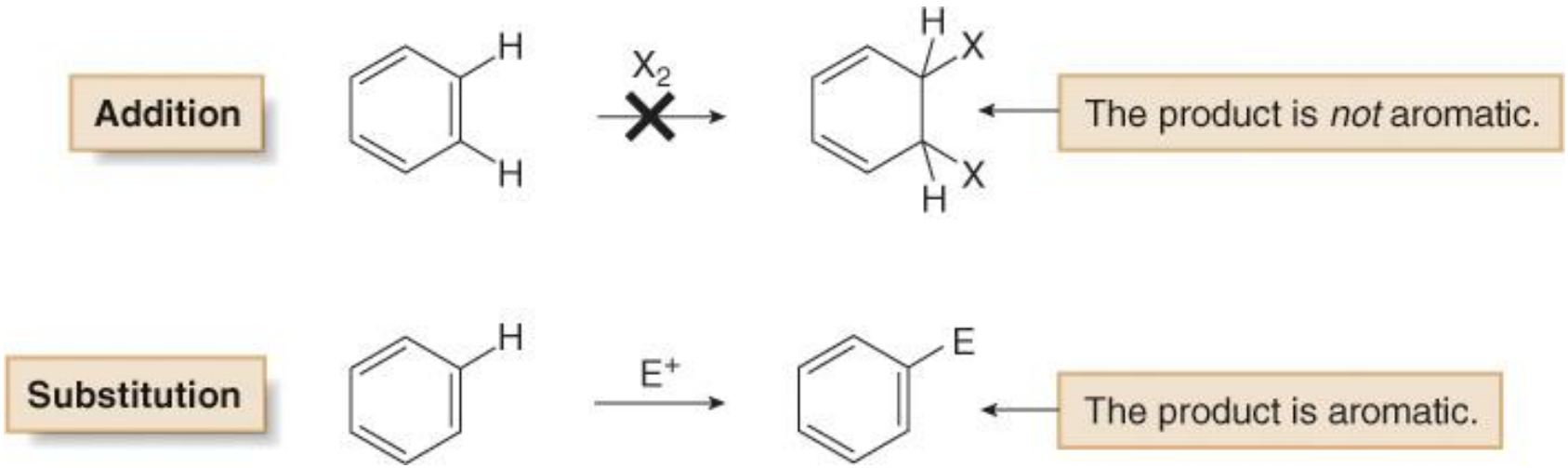
- Benzo[*a*]pyrene, produced by the incomplete oxidation of organic compounds in tobacco, is found in cigarette smoke.



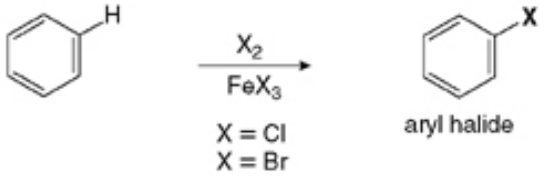
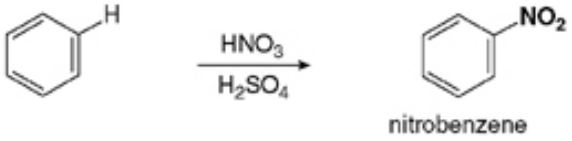
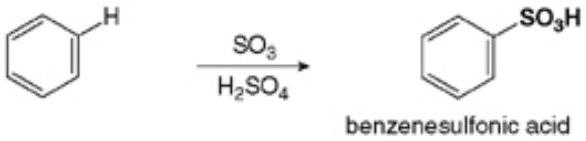
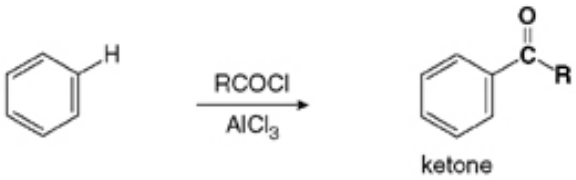
- When ingested or inhaled, benzo[a]pyrene and other similar PAHs are oxidized to carcinogenic products.

Electrophilic Aromatic Substitution

Introduction



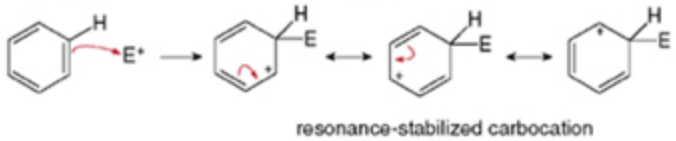
Introduction

Reaction	Electrophile
[1] Halogenation—Replacement of H by X (Cl or Br)	
	$E^+ = Cl^+$ or Br^+
[2] Nitration—Replacement of H by NO_2	
	$E^+ = \overset{+}{N}O_2$
[3] Sulfonation—Replacement of H by SO_3H	
	$E^+ = \overset{+}{S}O_3H$
[4] Friedel–Crafts alkylation—Replacement of H by R	
	$E^+ = R^+$
[5] Friedel–Crafts acylation—Replacement of H by RCO	
	$E^+ = R\overset{+}{C}O$

Mechanism

Mechanism 18.1 General Mechanism—Electrophilic Aromatic Substitution

Step [1] Addition of the electrophile (E⁺) to form a carbocation

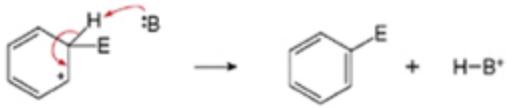


resonance-stabilized carbocation

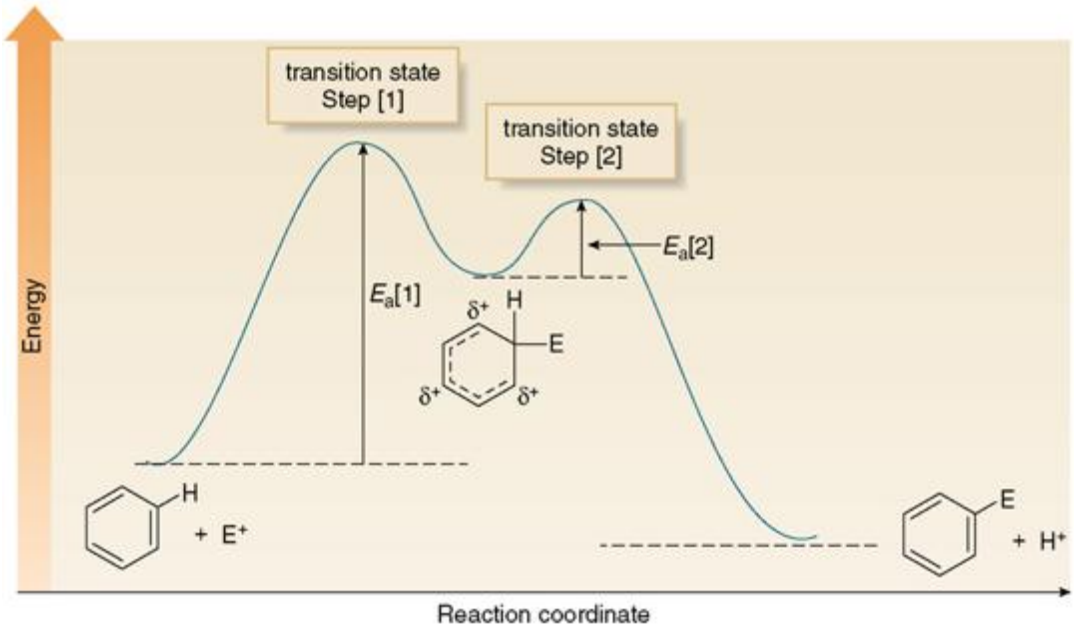
intermedio di Wheland

- Addition of the electrophile (E⁺) forms a new C–E bond using two π electrons from the benzene ring, and generating a carbocation. This carbocation intermediate is not aromatic, but it is resonance stabilized—**three resonance structures can be drawn.**
- Step [1] is rate-determining because the aromaticity of the benzene ring is lost.

Step [2] Loss of a proton to re-form the aromatic ring



- In Step [2], a base (B:) removes the proton from the carbon bearing the electrophile, thus re-forming the aromatic ring. This step is fast because the aromaticity of the benzene ring is restored.
- Any of the three resonance structures of the carbocation intermediate can be used to draw the product. The choice of resonance structure affects how curved arrows are drawn, but not the identity of the product.



Halogenation

Mechanism 18.2 Bromination of Benzene

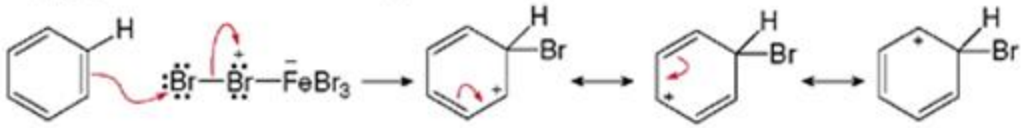
Step [1] Generation of the electrophile

Lewis base Lewis acid

electrophile
(serves as a source of Br^+)

- Lewis acid–base reaction of Br_2 with $FeBr_3$ forms a species with a weakened and polarized Br – Br bond. This adduct serves as a source of Br^+ in the next step.

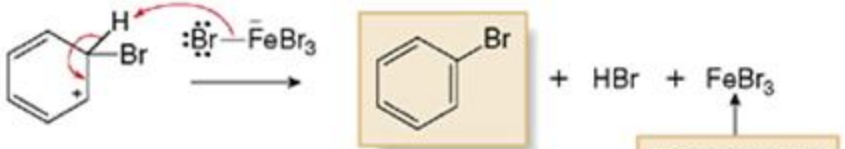
Step [2] Addition of the electrophile to form a carbocation



resonance-stabilized carbocation
+ $FeBr_4^-$

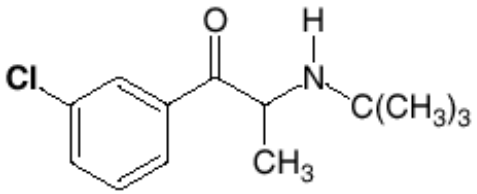
- Addition of the electrophile forms a new C – Br bond and generates a carbocation. This carbocation intermediate is resonance stabilized—**three resonance structures can be drawn.**
- The $FeBr_4^-$ also formed in this reaction is the base used in Step [3].

Step [3] Loss of a proton to re-form the aromatic ring

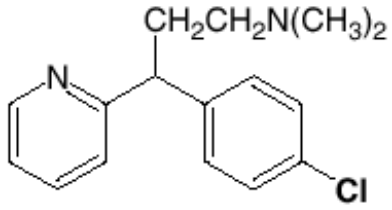


- $FeBr_4^-$ removes the proton from the carbon bearing the Br, thus re-forming the aromatic ring.
- $FeBr_3$, a catalyst, is also regenerated for another reaction cycle.

Halogenation

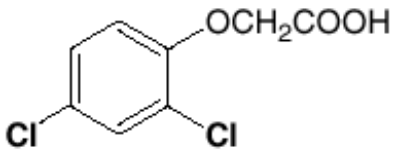


Generic name: **bupropion**
Trade names: **Wellbutrin, Zyban**
antidepressant,
also used to reduce nicotine cravings

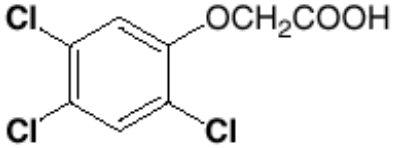


chlorpheniramine
antihistamine

Herbicides were used extensively during the Vietnam War to defoliate dense jungle areas. The concentration of certain herbicide by-products in the soil remains high today.



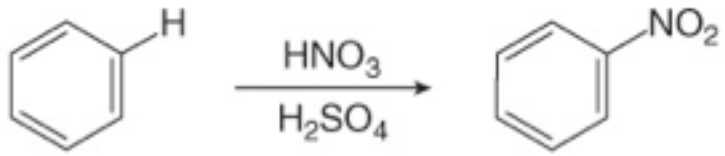
2,4-D
2,4-dichlorophenoxy-
acetic acid
herbicide



2,4,5-T
2,4,5-trichlorophenoxy-
acetic acid
herbicide

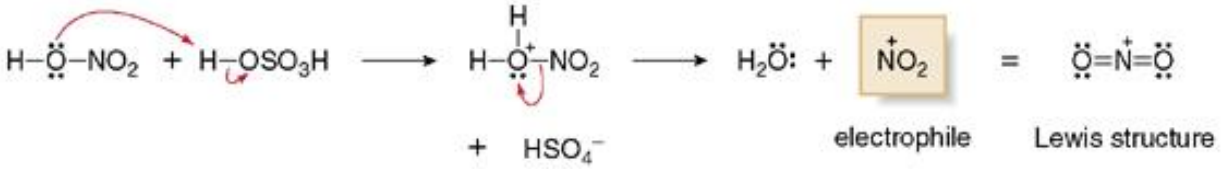
the active components in **Agent Orange**,
a defoliant used in the Vietnam War

Nitration



nitrobenzene

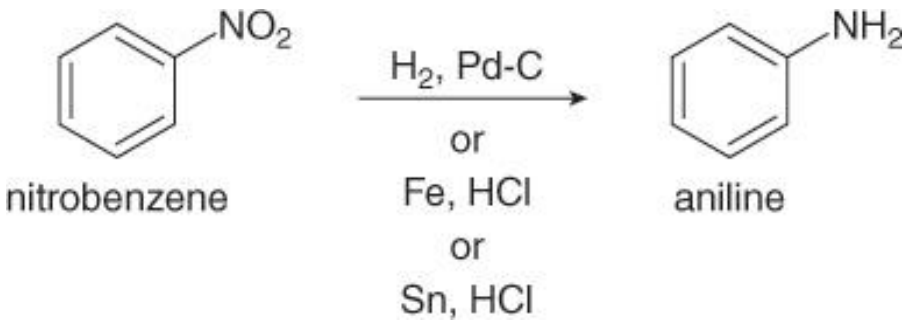
Mechanism 18.3 **Formation of the Nitronium Ion ($^{+}NO_2$) for Nitration**



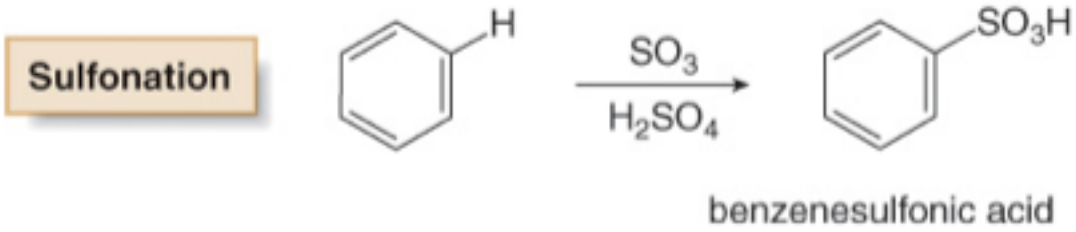
ione nitronio

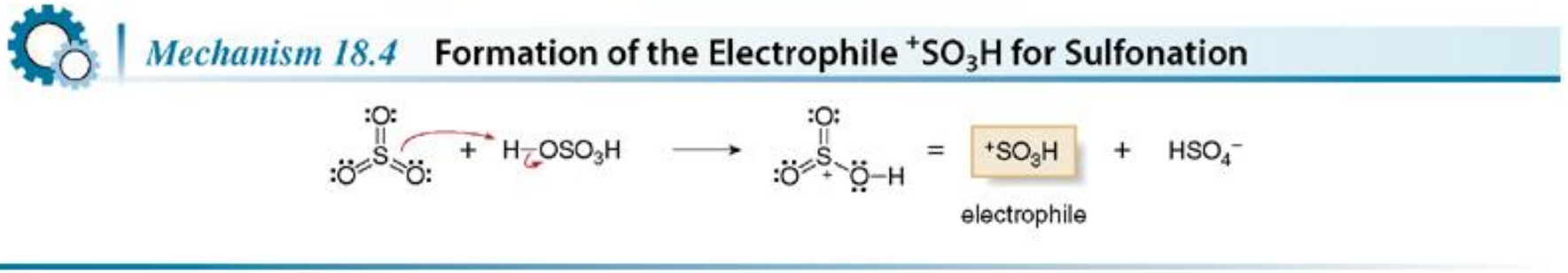
Nitro Group Reduction

Aromatic nitro groups (NO_2) can readily be reduced to amino groups (NH_2) under a variety of conditions.



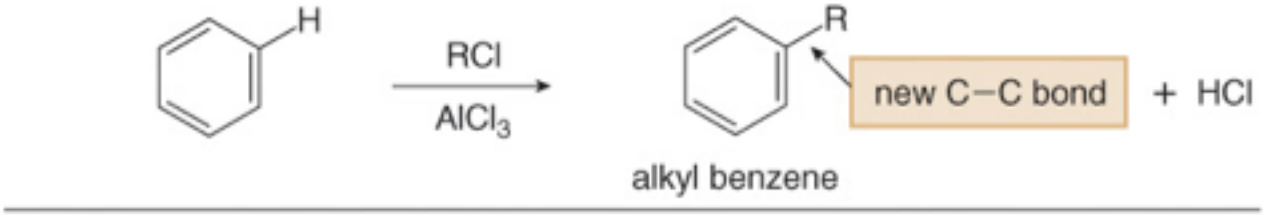
Sulfonation

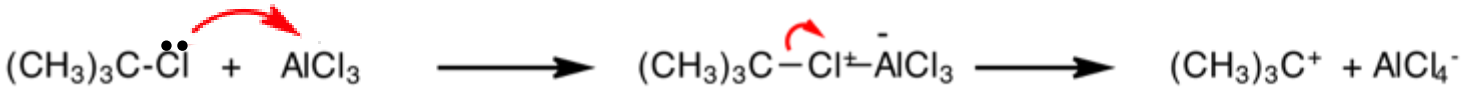


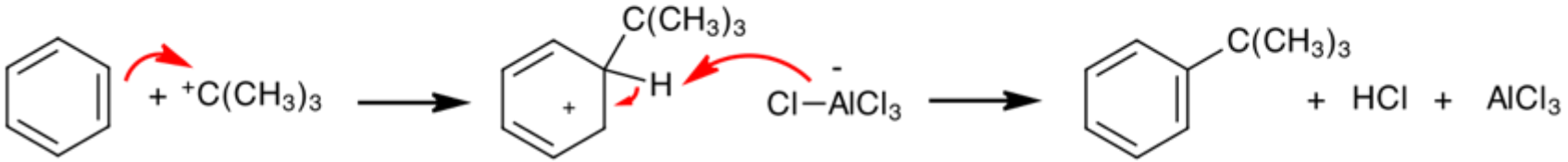


oleum: acido solforico concentrato addizionato di SO_3

Friedel-Crafts Alkylation





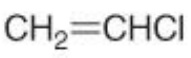


Best with 2ry and 3ry halides

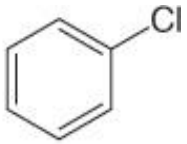
Limitations

[1] Vinyl halides and aryl halides do not react in Friedel-Crafts alkylation.

Unreactive halides in the Friedel–Crafts alkylation

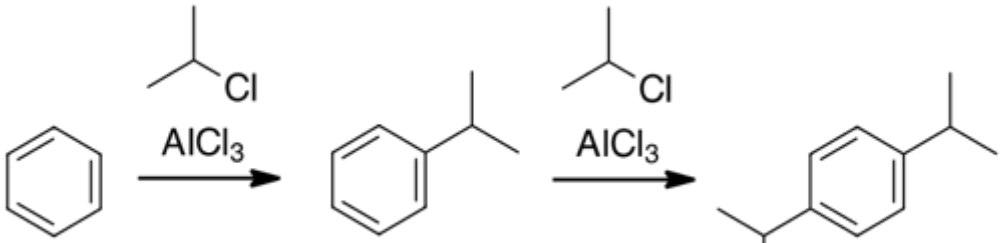


vinyl halide



aryl halide

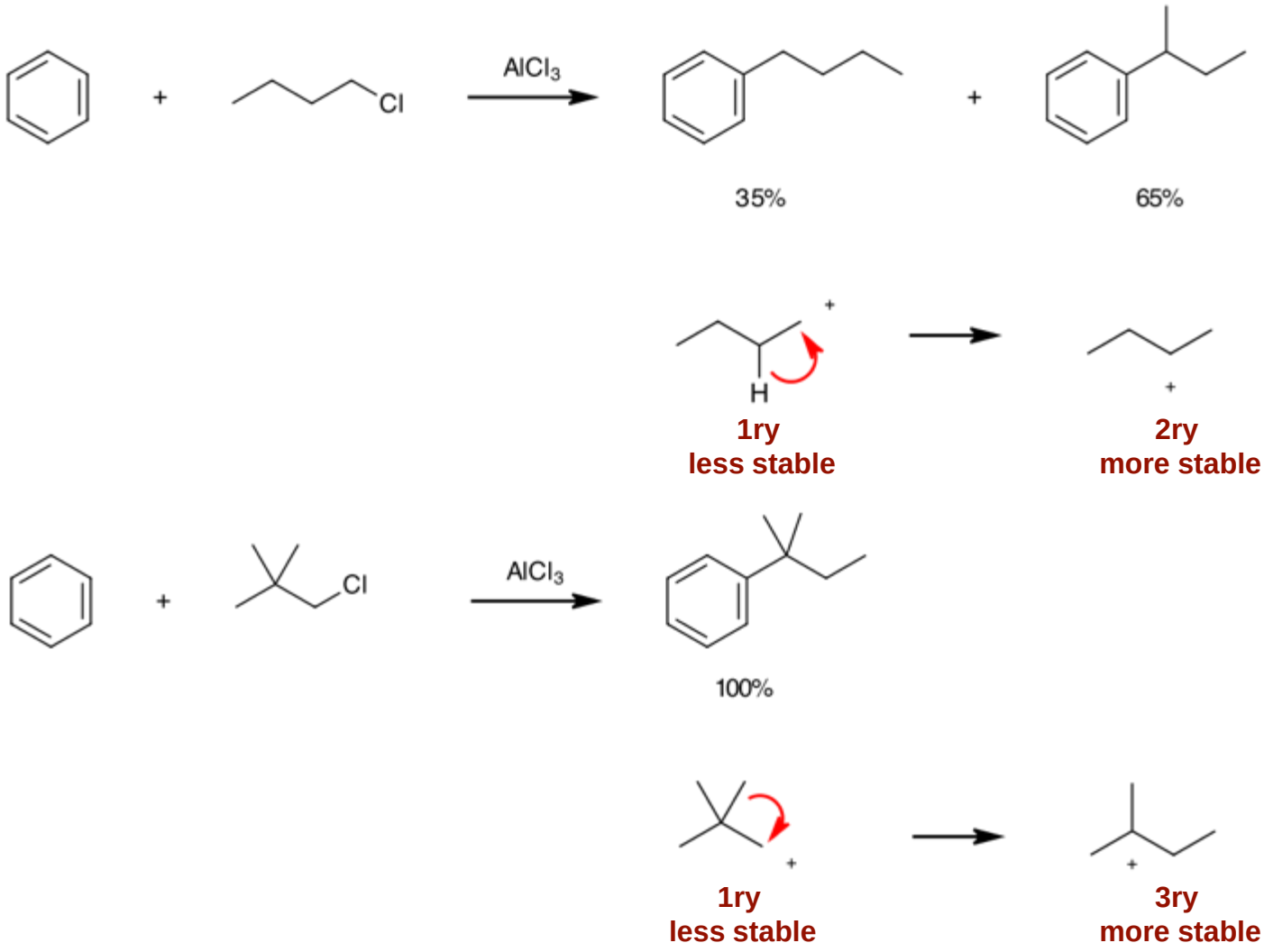
[2] Disubstituted products are obtained in F.-C. alkylations, but not in acylations.



More reactive than benzene

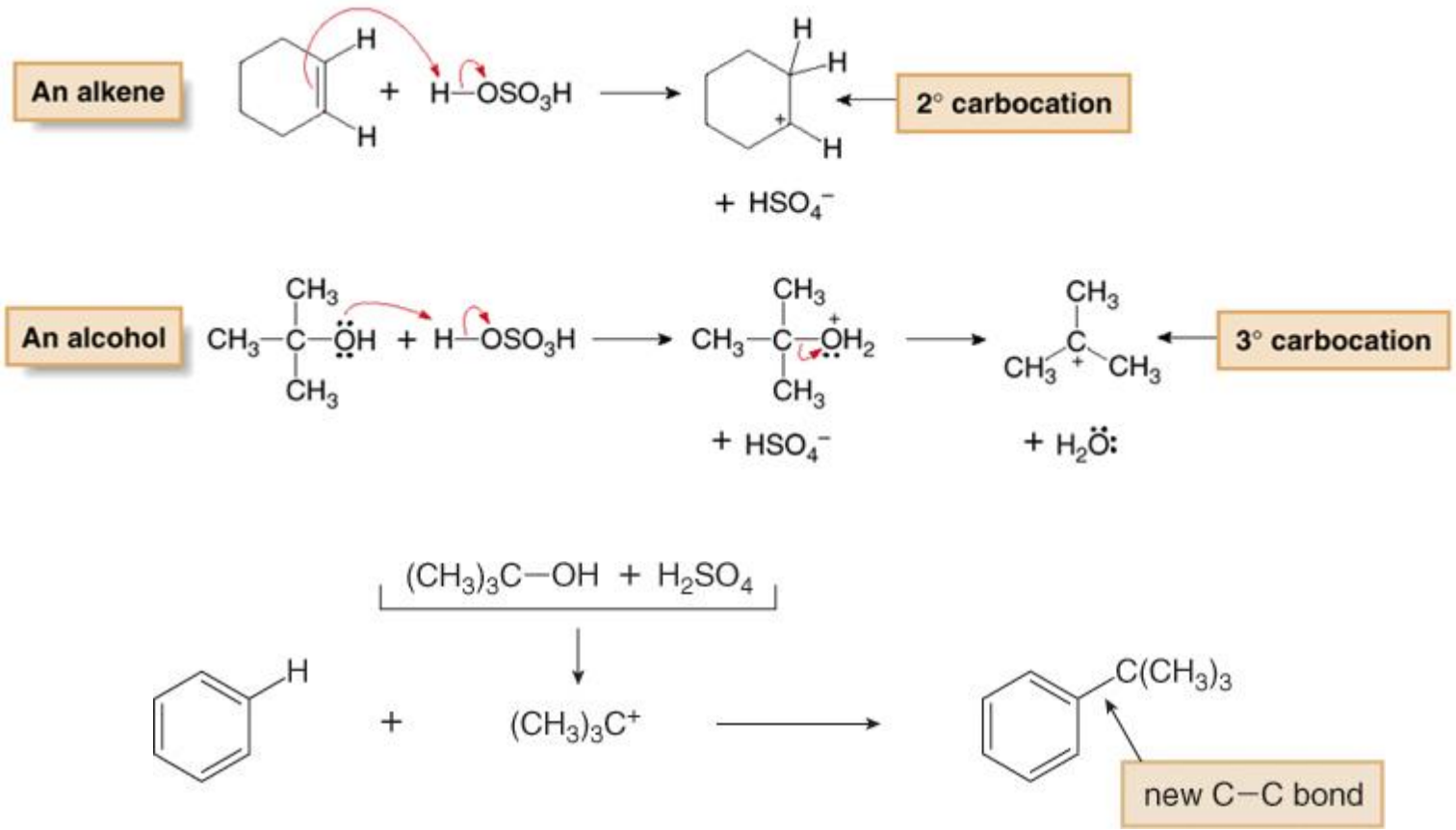
Limitations

[3] Rearrangements can occur.

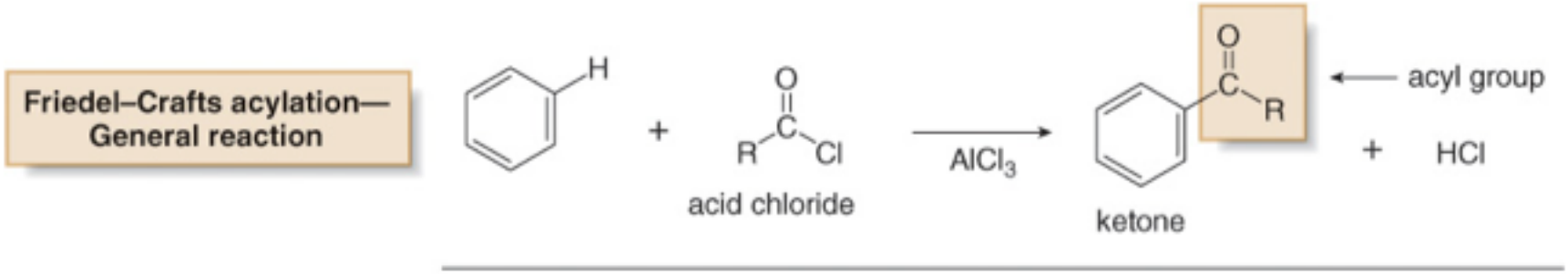


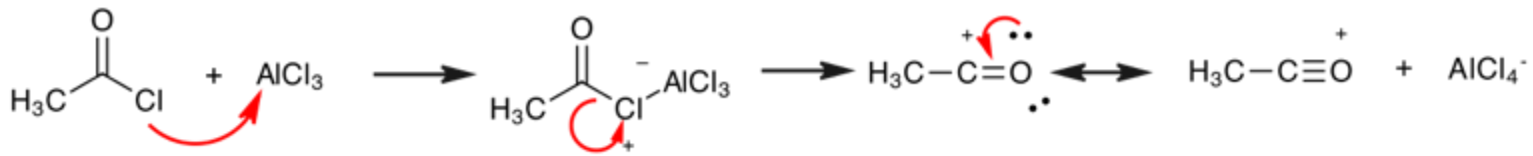
Friedel-Crafts Alkylation

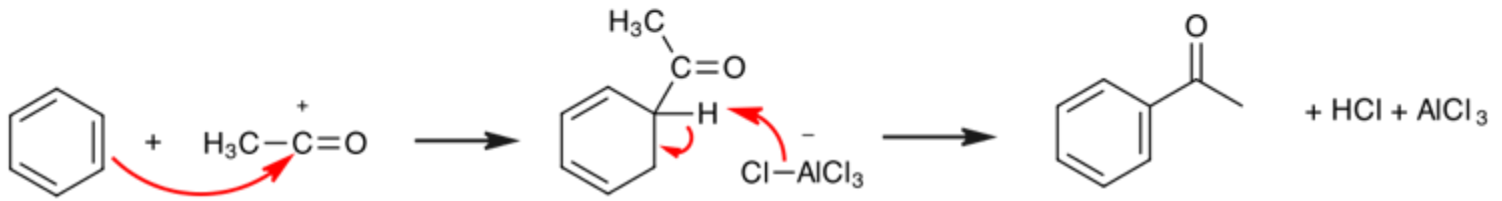
Other functional groups that form carbocations can also be used as starting materials.



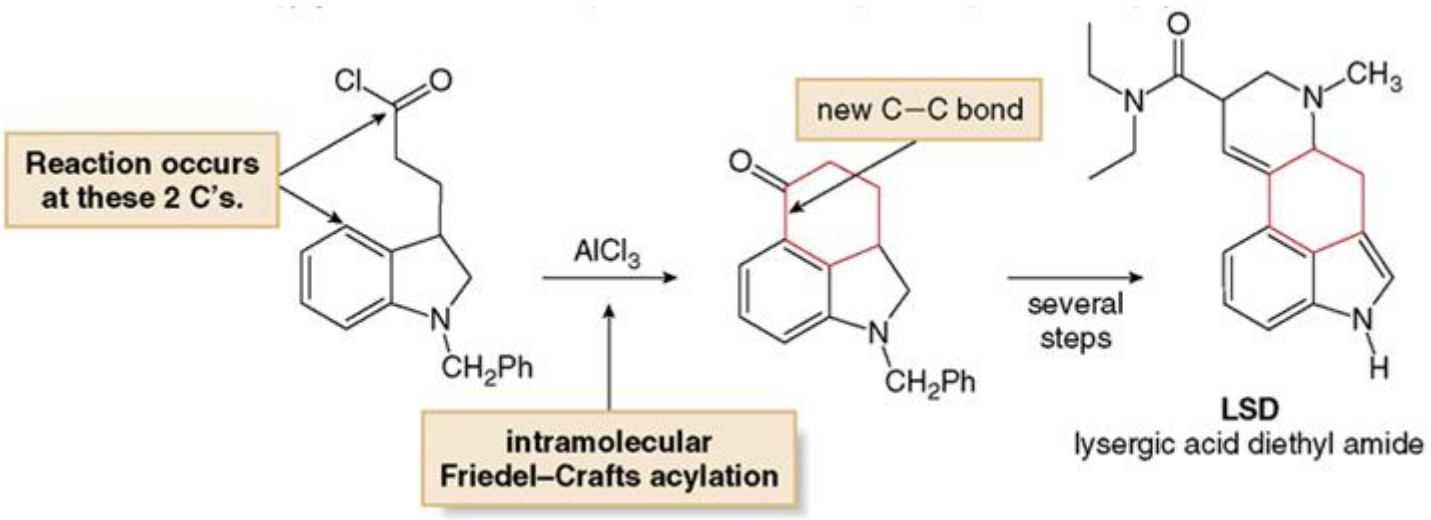
Friedel-Crafts Acylation



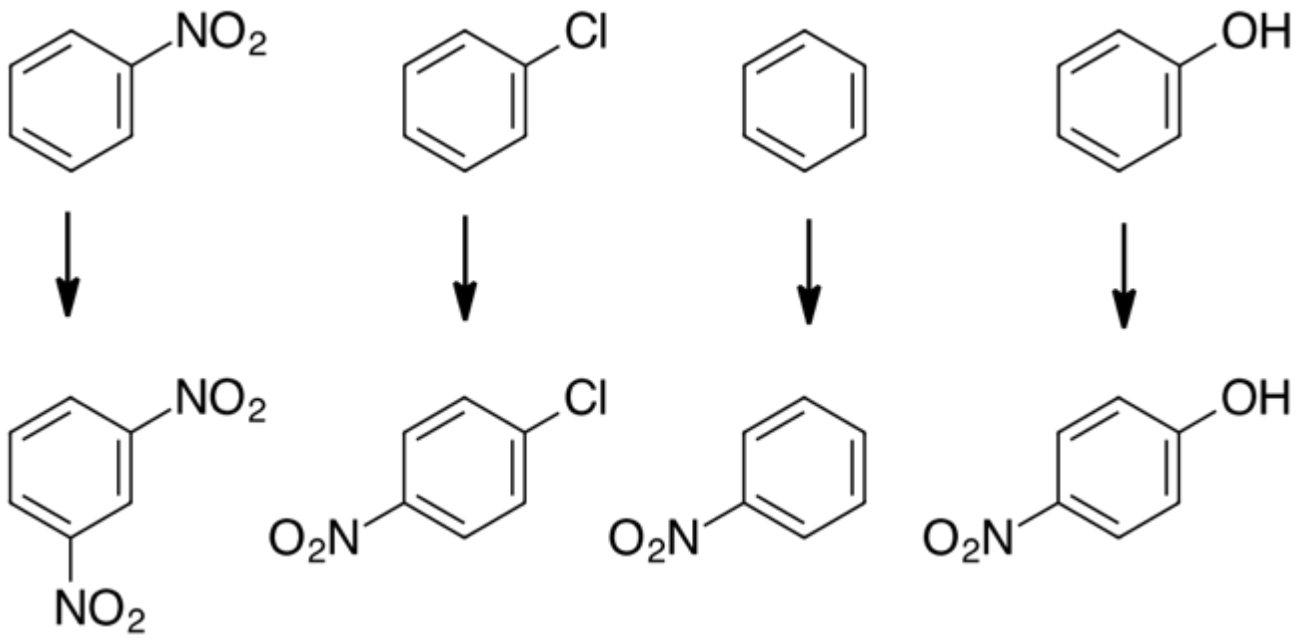




Intramolecular Friedel-Crafts reactions



Nitration of Substituted Benzenes



Relative rates	6×10^{-8}	0.033	1	1000

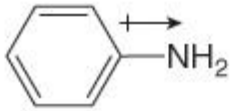
Substituents modify the electron density in the benzene ring, and this affects the course of electrophilic aromatic substitution.

Substituted Benzenes

Inductive effects (through σ bonds):

- Atoms more electronegative than carbon—including N, O, and X—pull electron density away from carbon and thus exhibit an electron-withdrawing inductive effect.
- Polarizable alkyl groups donate electron density, and thus exhibit an electron-donating inductive effect.

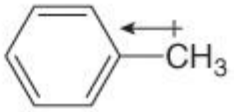
Electron-withdrawing inductive effect



- I

- N is **more electronegative** than C.
- N inductively withdraws electron density.

Electron-donating inductive effect



+ I

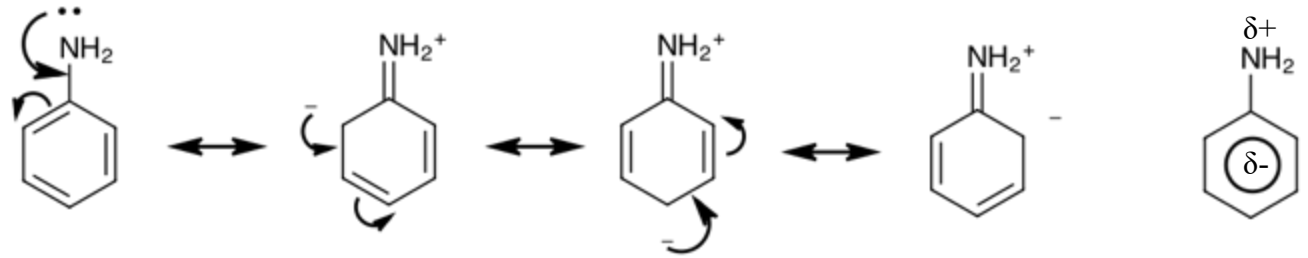
- Alkyl groups are **polarizable,** making them electron-donating groups.

- I	$-NH_3^+$ $-CF_3$	-NH2, -NHR $-NR_2$	-OH -OR	-F -Cl -Br -I	-CHO -COR -COOH -COOR	-CN	SO_3H SO_2R	$-NO_2$
+ I	$-CH_3$ -Alkyl $-SiR_3$ SiR_3							

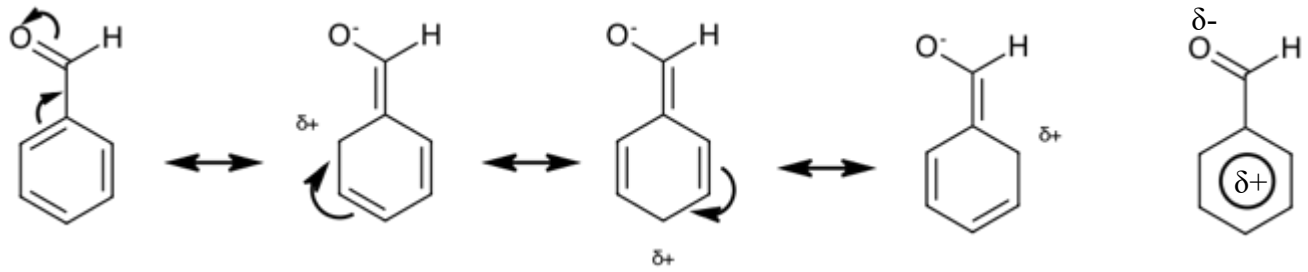
Substituted Benzenes

Resonance effects (through π bonds) are only observed with substituents containing lone pairs or π bonds.

- Substituents containing lone pairs are electron donating **(+ R)**



- Substituents –Y=Z (C_6H_5-Y=Z), where Z is more electronegative than Y are electron accepting **(- R)**

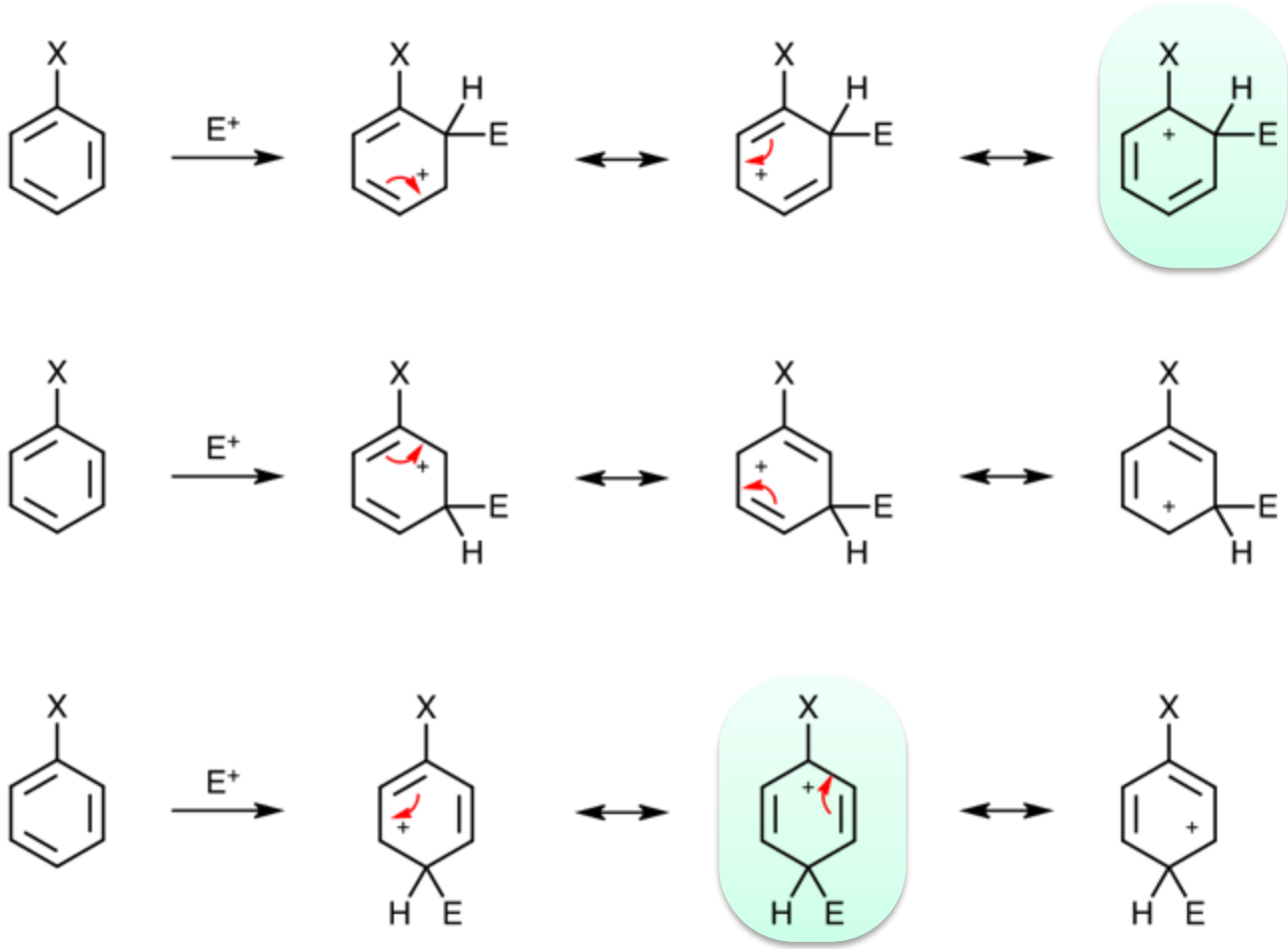


Substituted Benzenes: Activation

		+ R			- R			
		+R > -I		-I >+R				
- I	$-NR_3+$ CF_3	$-NH_2$, -NHR $-NR_2$	-OH -OR	-F -Cl -Br -I	-CHO -COR -COOH -COOR	CN	SO_3H SO_2R	$-NO_2$
+ I	$-CH_3$ -Alkyl $-SiR_3$							

- Substituents that increase the electron density on the ring activate the ring towards electrophiles. Substituents that decrease the electron density on the ring deactivate the ring towards electrophiles.
- To predict whether a substituted benzene is more or less electron rich than benzene itself, we must consider the net balance of both the inductive and resonance effects.

Substituted Benzenes: Orientation

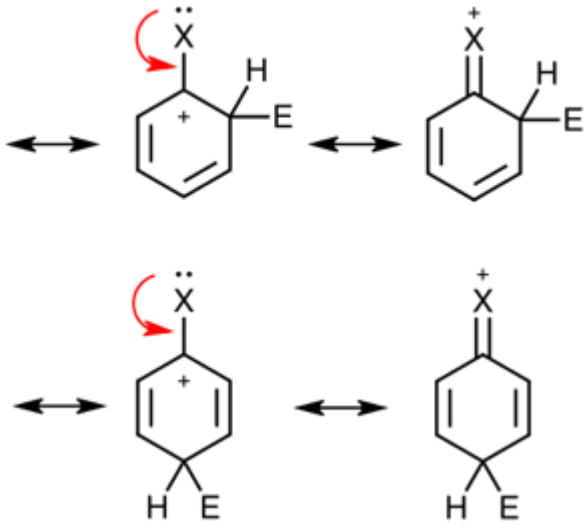


If the reaction takes place in the ortho or para positions a positive charge develops on the carbon atom adjacent to the substituent.

Substituted Benzenes: Orientation

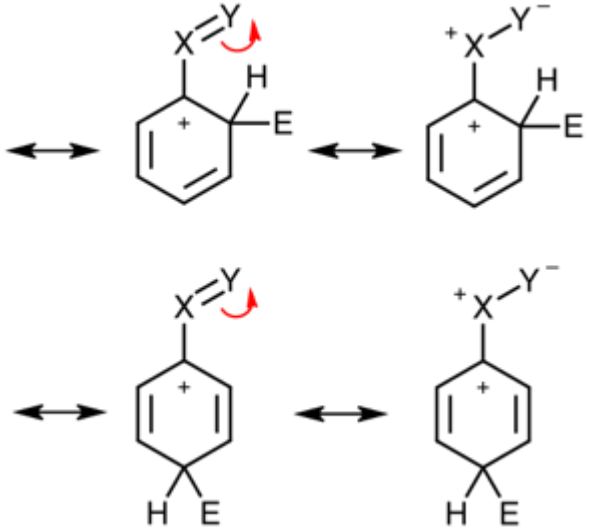
+ R

-o, -p intermediates are resonance stabilised



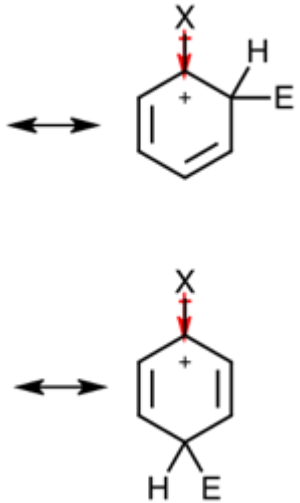
- R

-o, -p intermediates are resonance destabilised



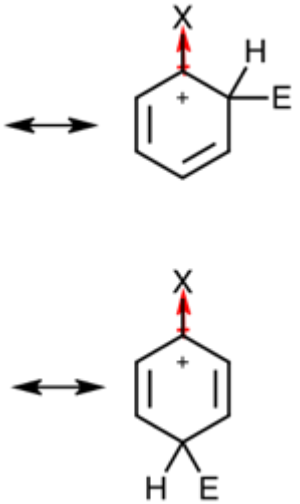
+ I

-o, -p intermediates are inductively stabilised



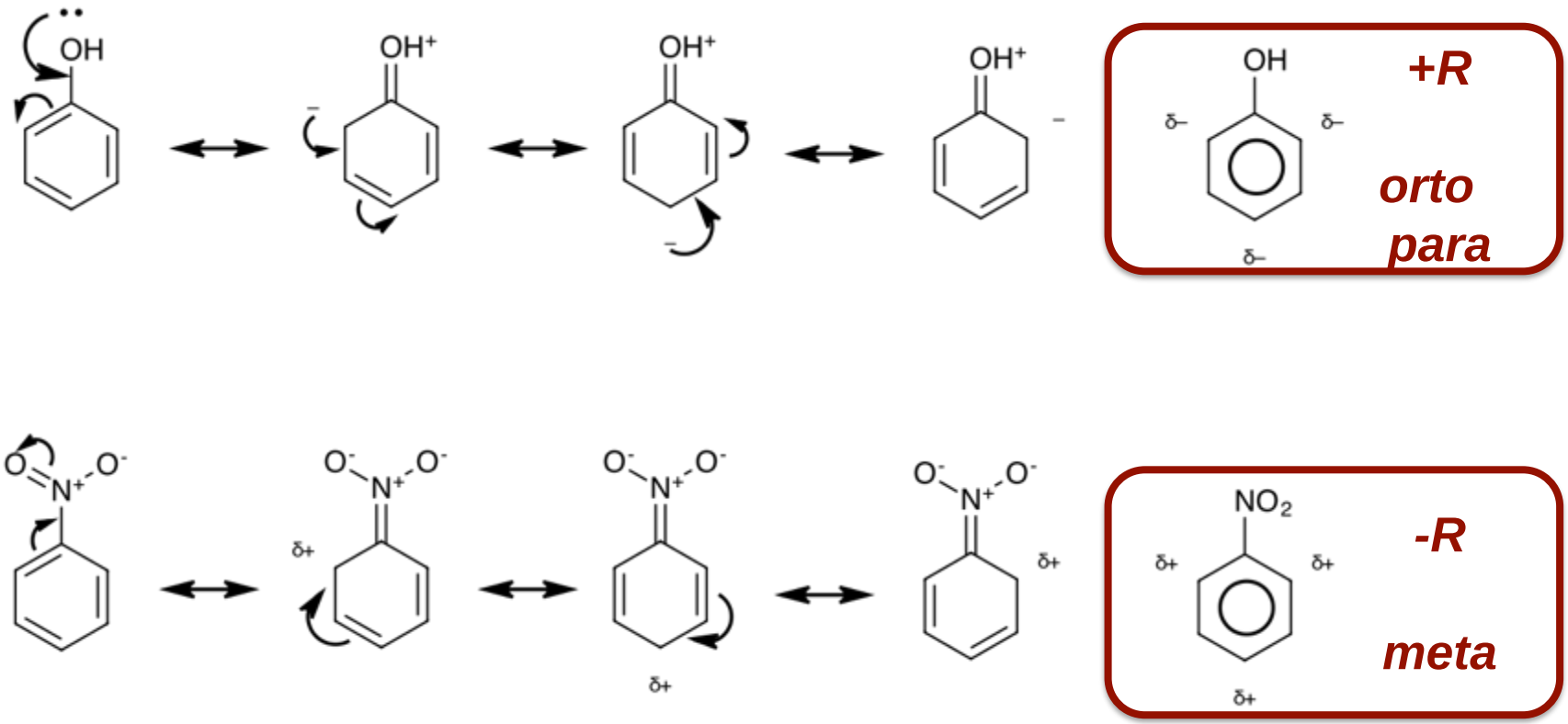
- I

-o, -p intermediates are inductively destabilised



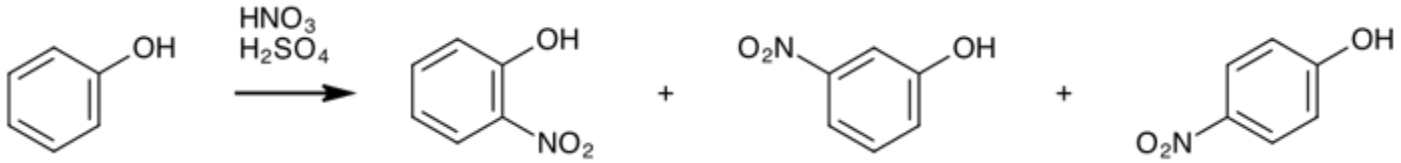
Substituted Benzenes: Orientation

The new group is located either ortho, meta, or para to the existing substituent. The resonance effect of the first substituent determines the position of the second incoming substituent



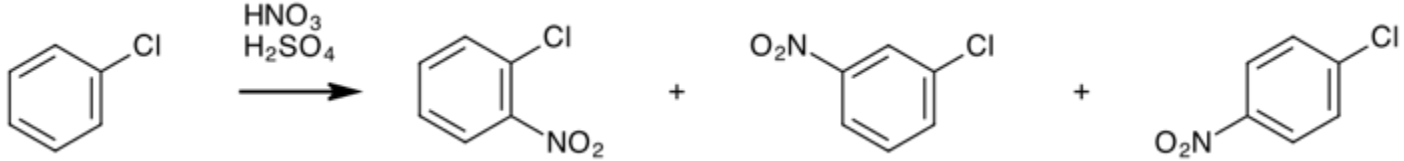
Substituted Benzenes: Orientation

+R > -I (-OR, -NR2): activating, o- p- directing



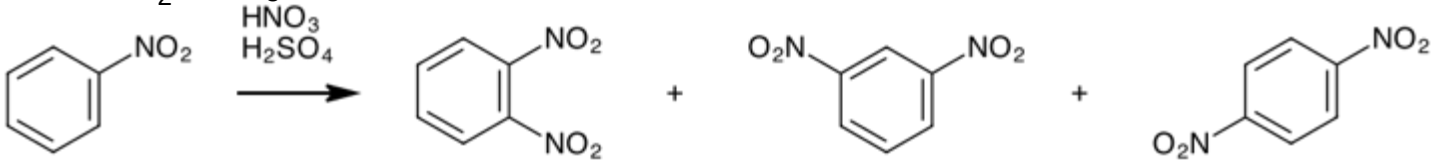
30% traces 70%

-I > +R (-F, -Cl, -Br, -I): deactivating, o- p- directing



35% traces 65%

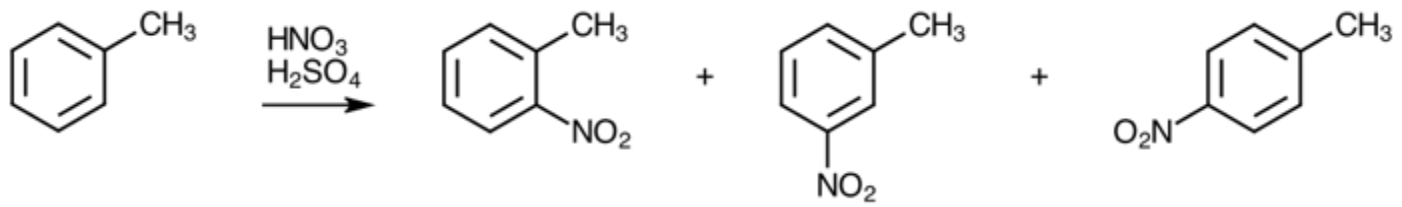
-I, -R (-NO_2, -SO_3H, -CN, -COR): deactivating, m- directing.



5% 90% 5%

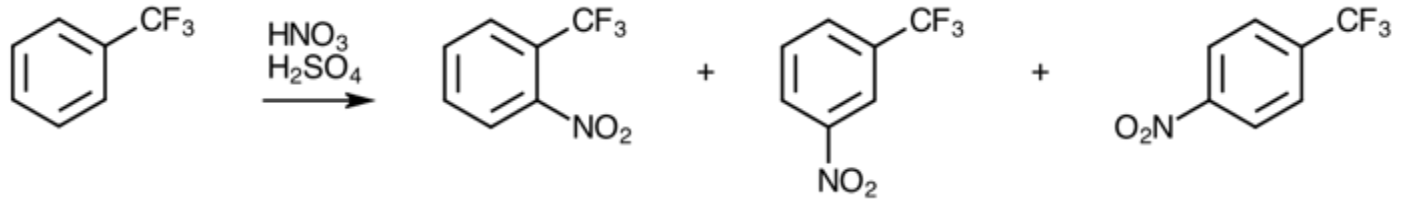
Substituted Benzenes: Orientation

+ I: activating, -o -p directing (same as + R)



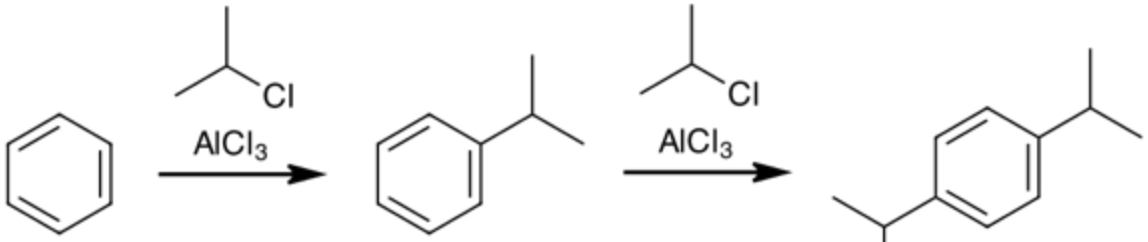
58% 5% 37%

- I: deactivating, -m directing (same as - R)

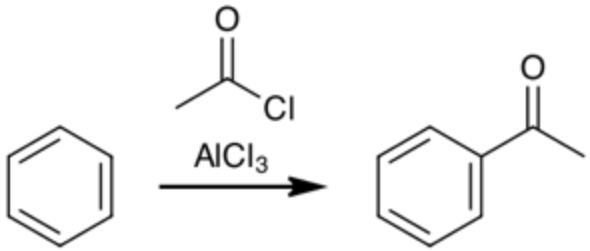


6% 91% 3%

Substituted Benzenes: Activation

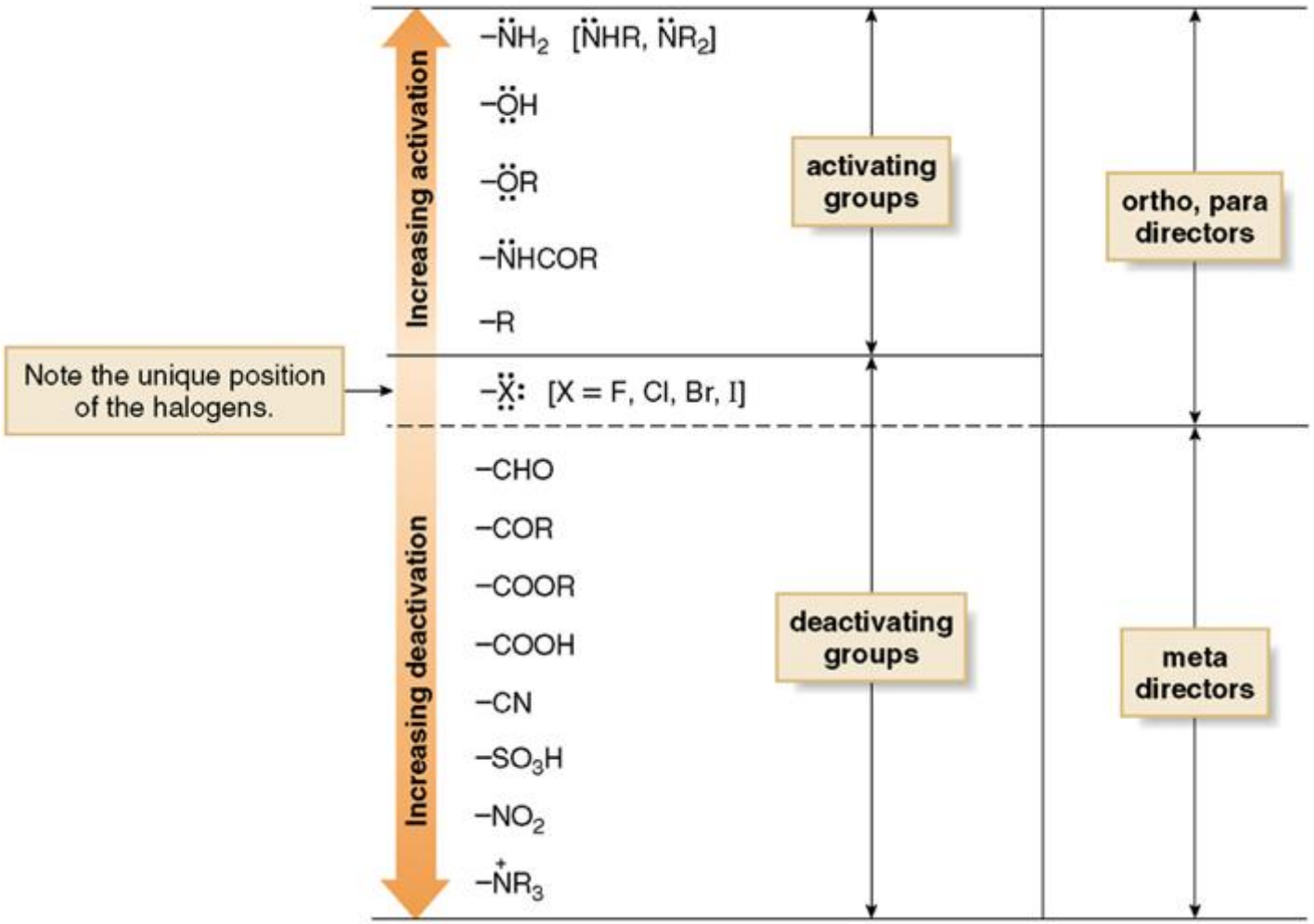


More reactive
than benzene

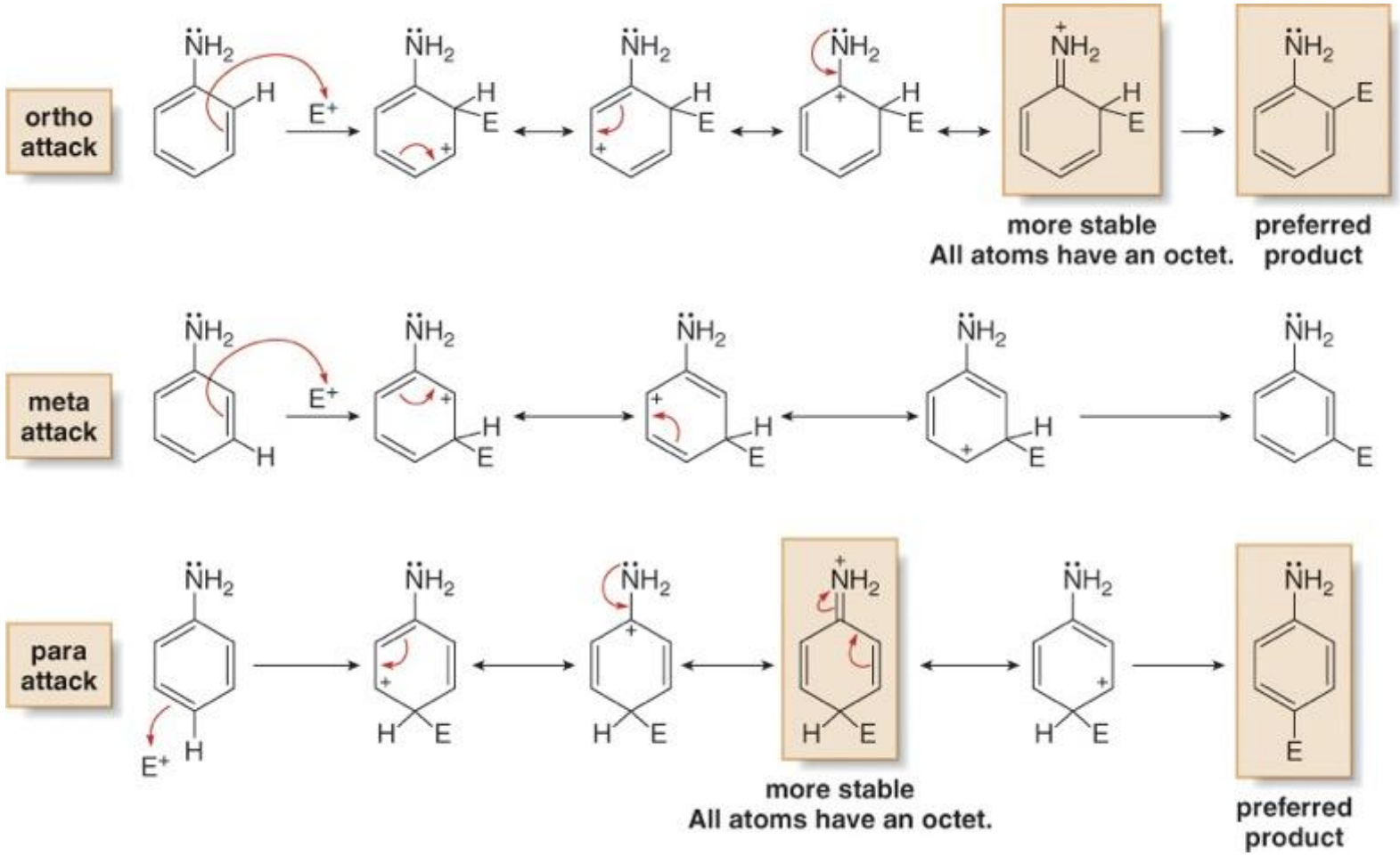


Less reactive
than benzene

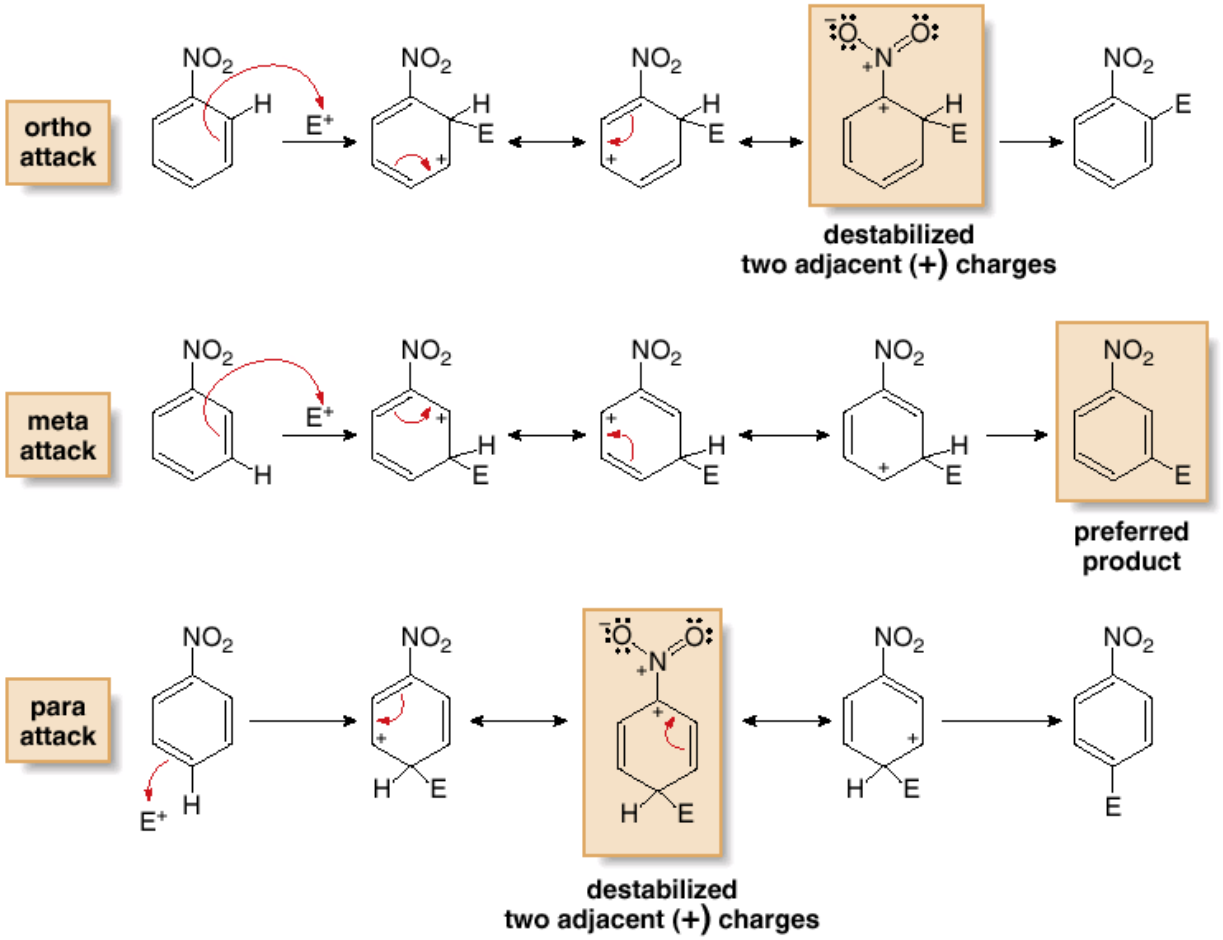
Substituent Effects. Summary



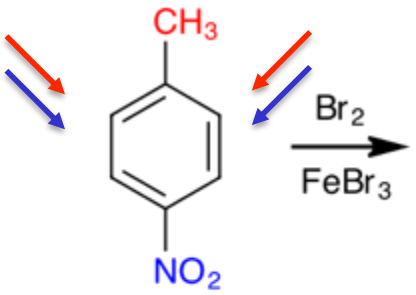
Substituent Effects. Alternative Explanation

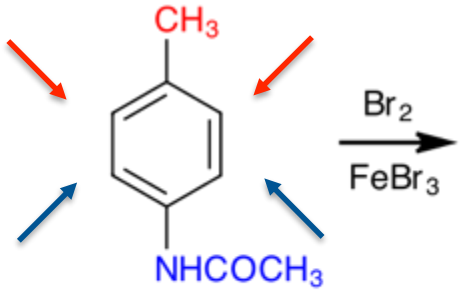


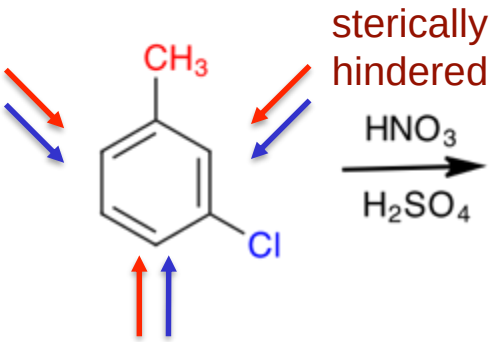
Substituent Effects. Alternative Explanation



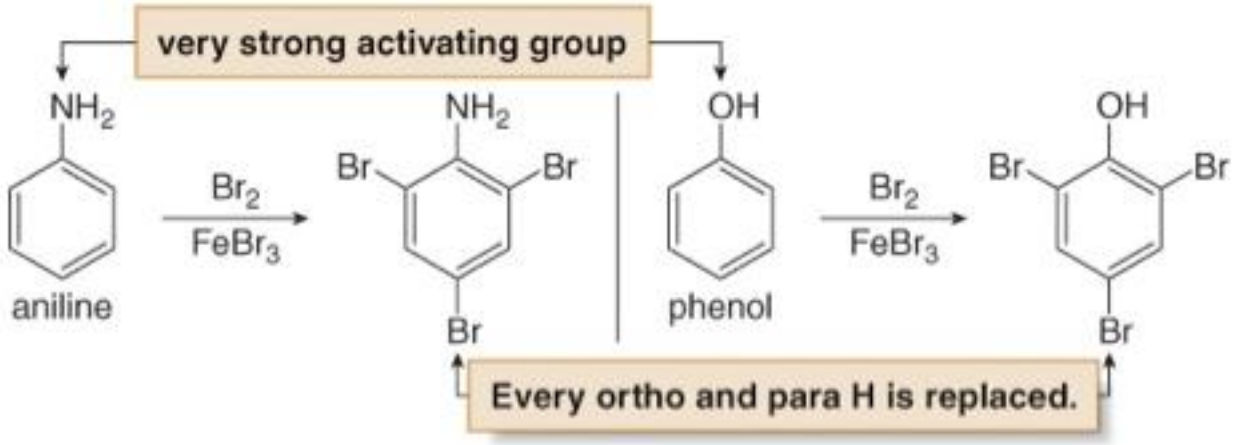
Disubstituted Benzenes

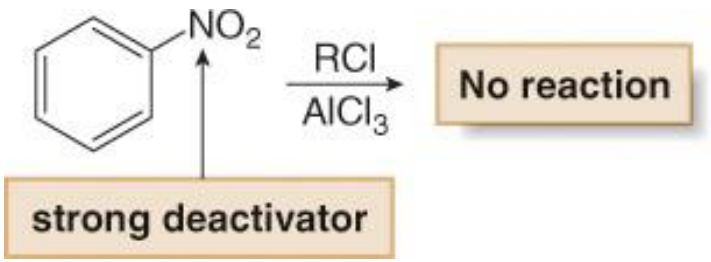




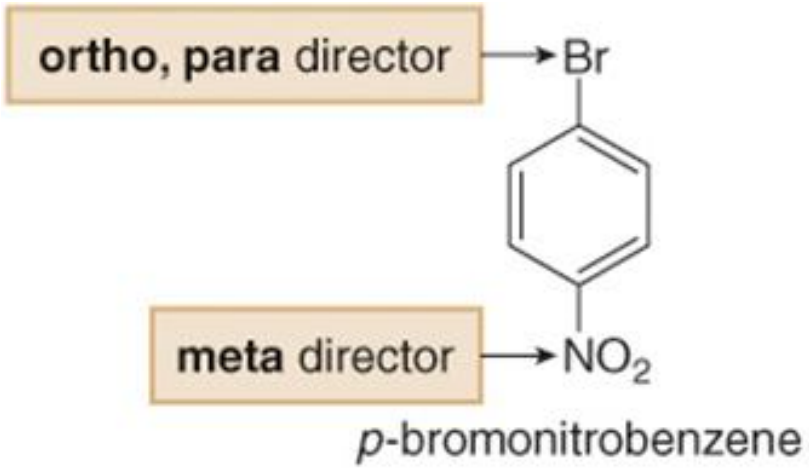


Further Examples





Synthesis of Polysubstituted Benzenes



p-bromonitrobenzene

Synthesis of Polysubstituted Benzenes

Pathway [1]: Bromination before nitration

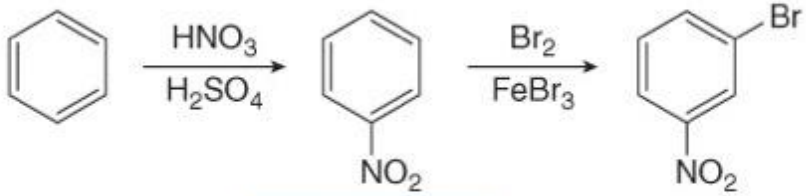
ortho, para director

para product

The ortho isomer can be separated from the mixture.

This pathway gives the desired product.

Pathway [2]: Nitration before bromination

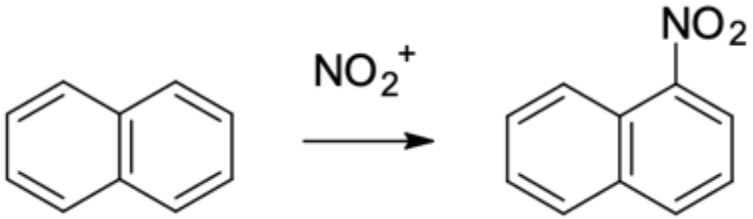


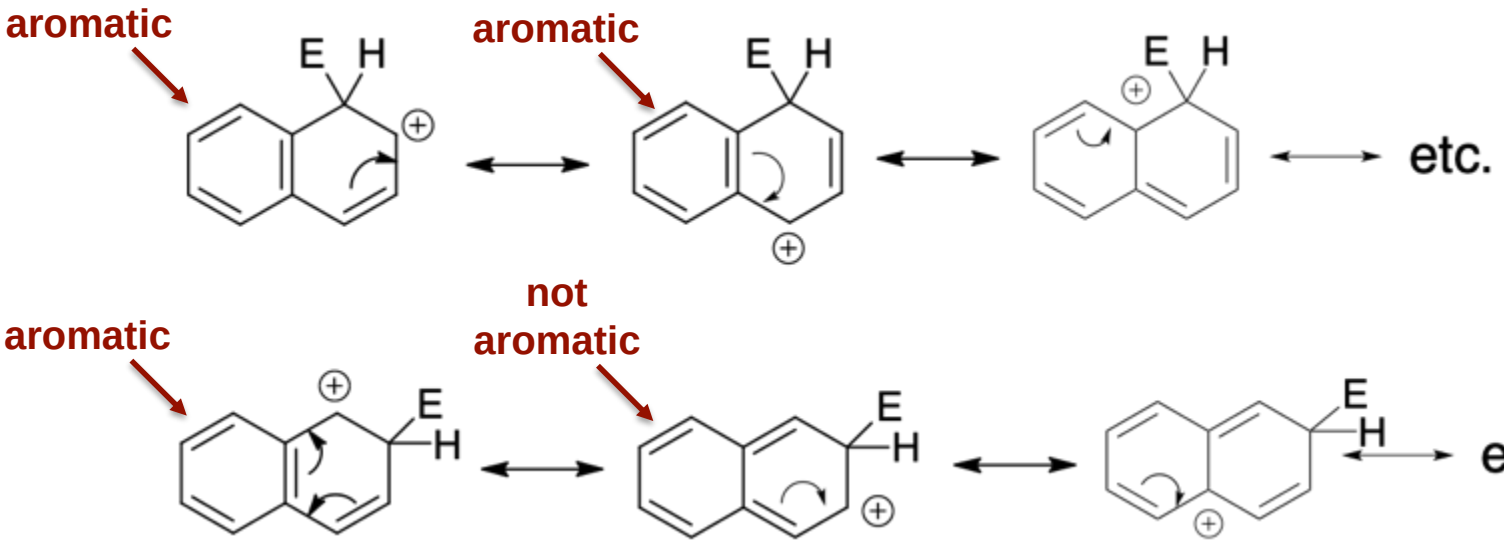
meta director

meta isomer

This pathway does NOT form the desired product.

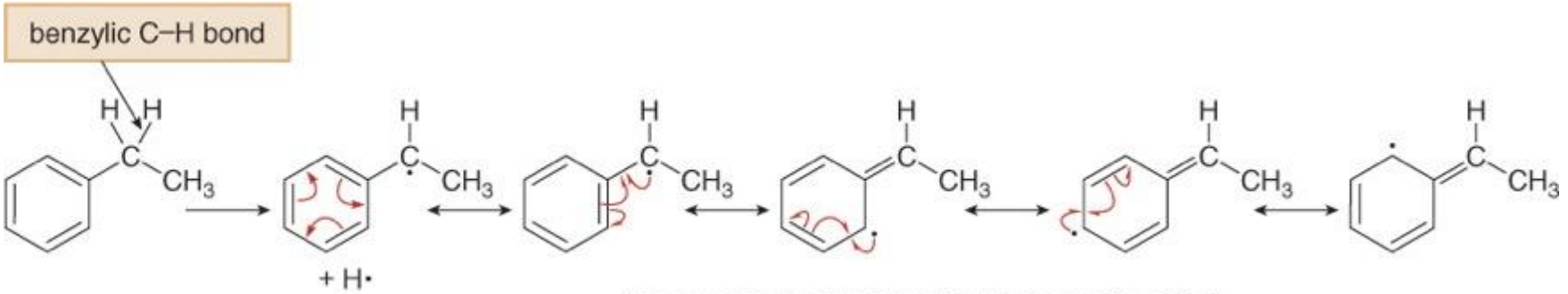
S_EAr in Polyciclic Aromatic Compounds



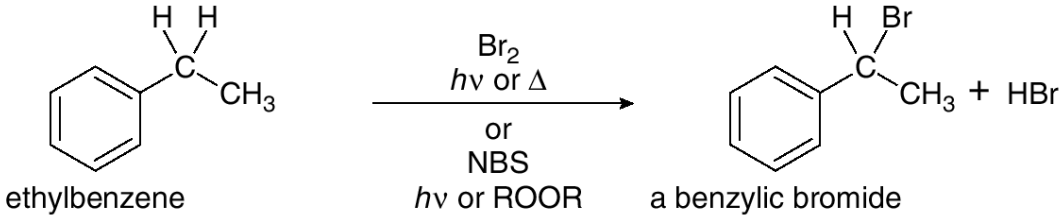


Side Chain Reactivity: Radical Halogenation

Benzylic C—H bonds are weaker than most other sp^3 hybridized C—H bonds, because homolysis forms a resonance-stabilized benzylic radical.



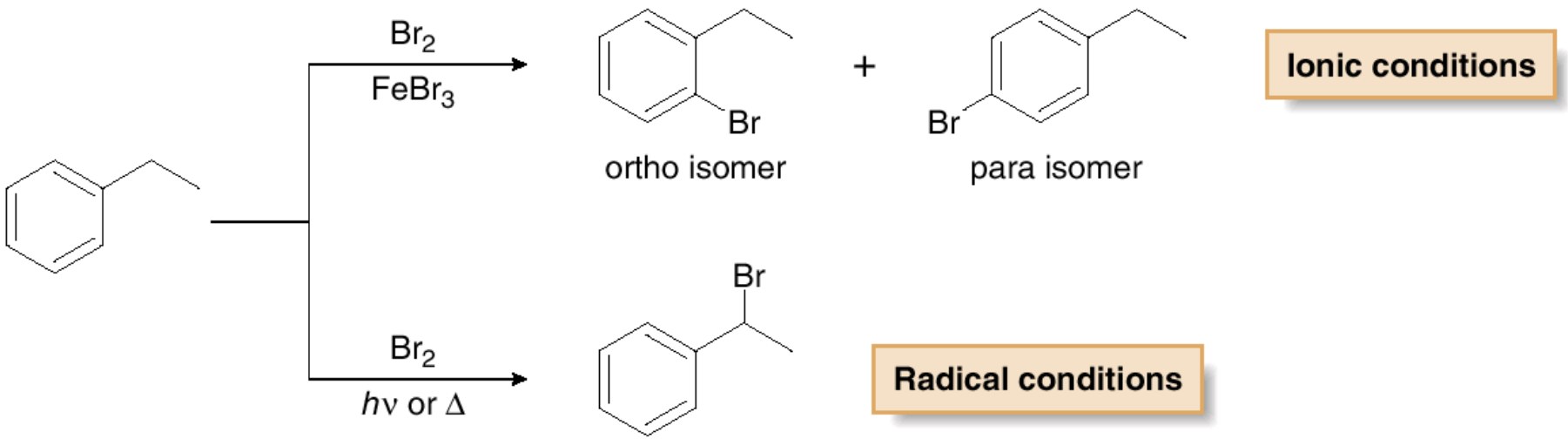
five resonance structures for the benzylic radical



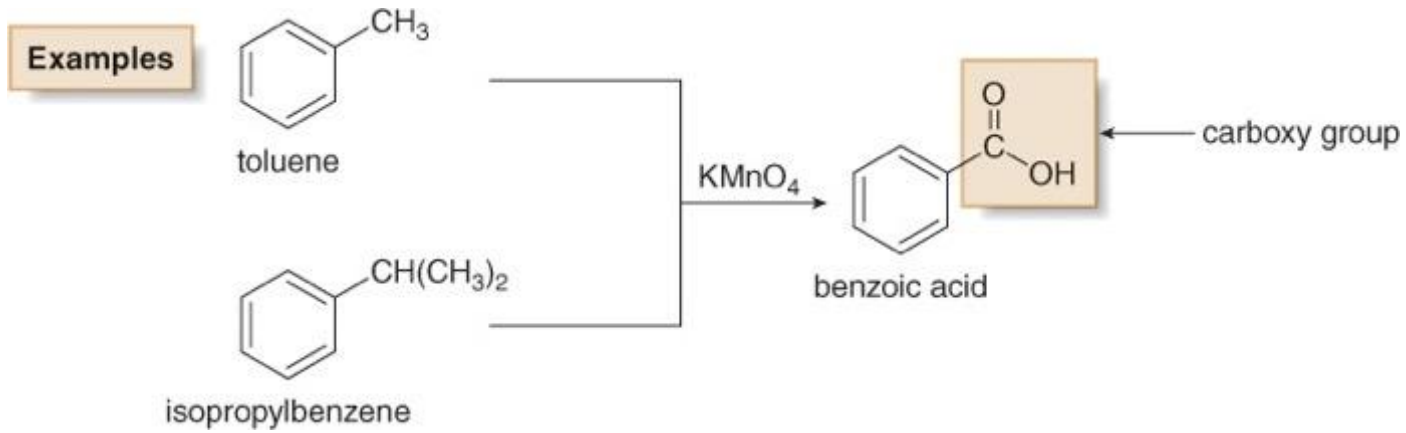
ethylbenzene — a benzylic bromide

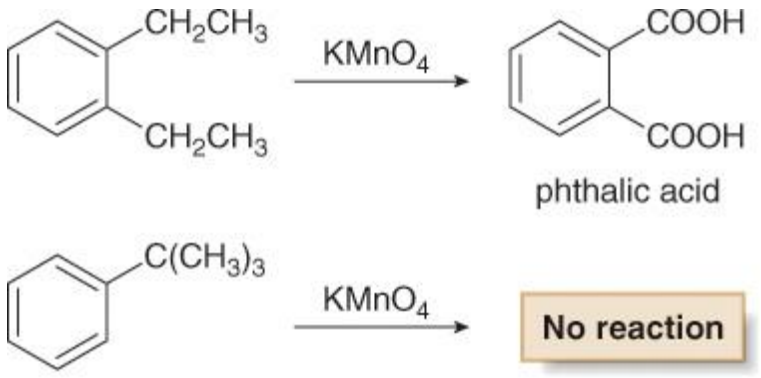
radical conditions

Side Chain Reactivity

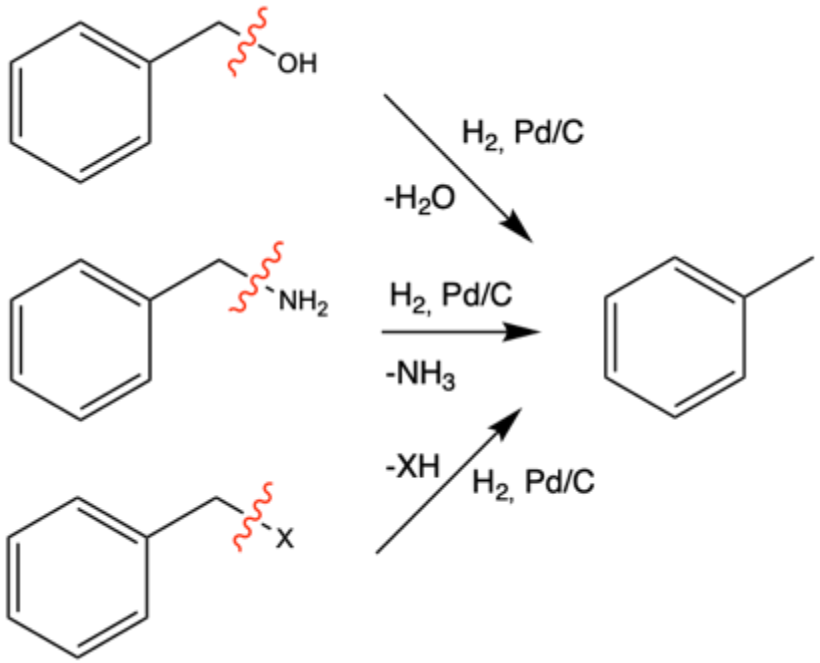


Side Chain Reactivity: Oxidation

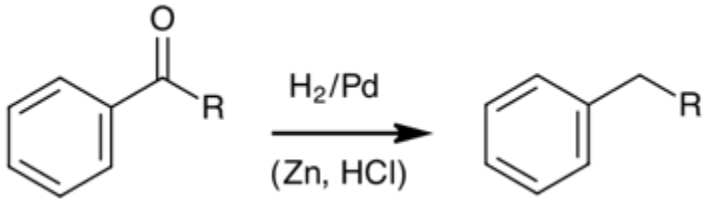


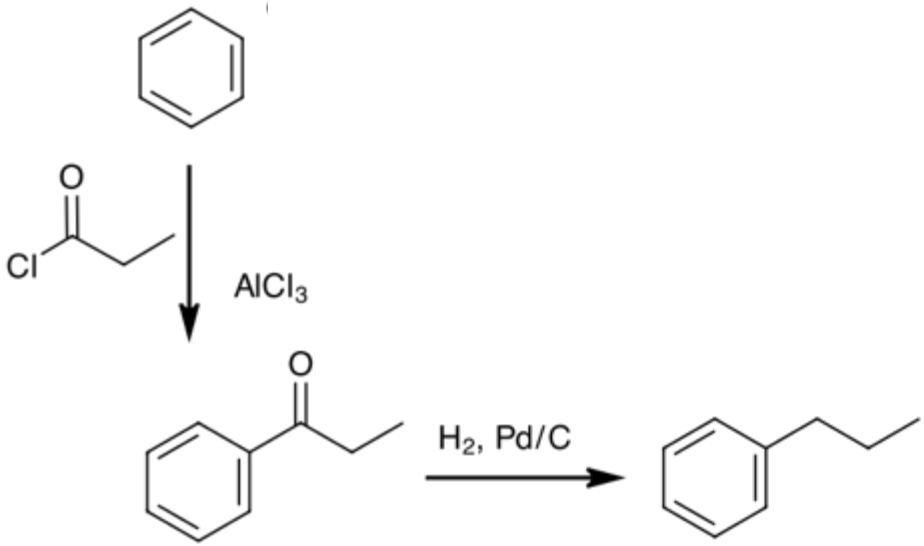


Side Chain Reactivity: Reduction

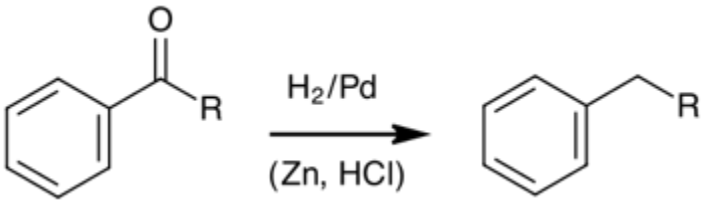


Side Chain Reactivity: Reduction

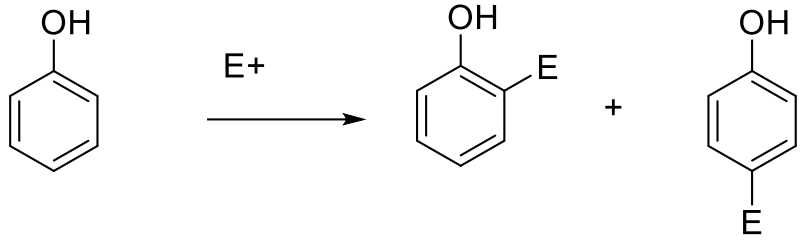




Side Chain Reactivity: Reduction

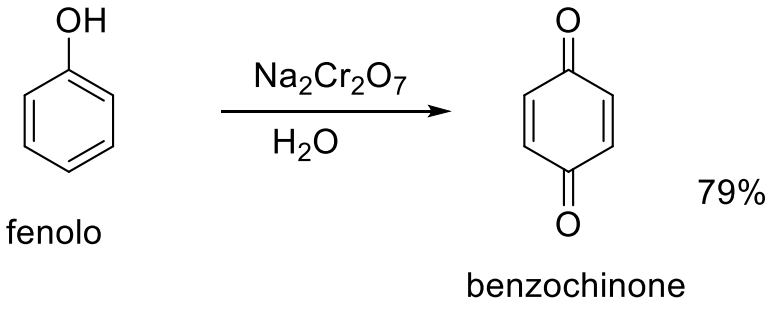


Reattività di fenoli



molto reattivi in SEAr

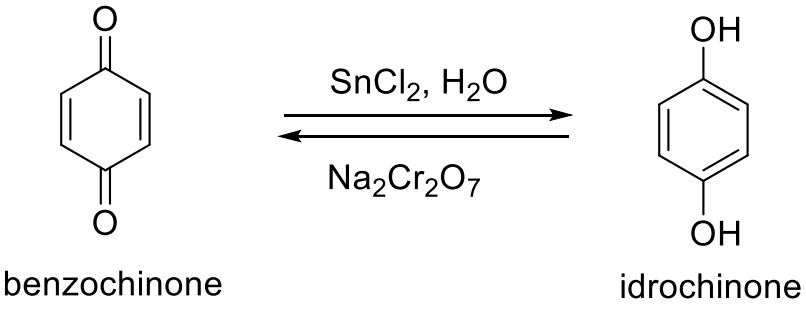
ossidazione



fenolo

benzochinone

79%



benzochinone

idrochinone