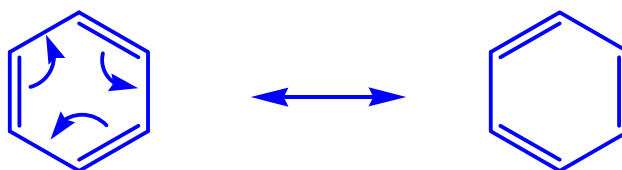


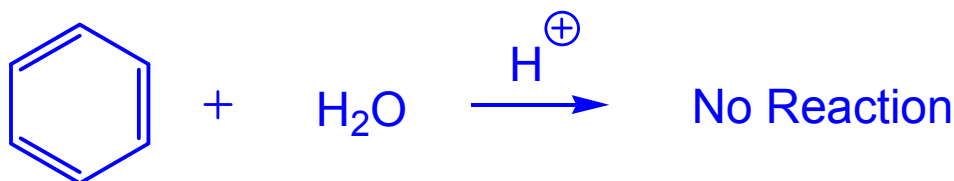
9. Benzene and Derivatives (text 9.1 – 9.7 and 9.9)

A. Structure

- The compound benzene, C_6H_6 , discovered by Michael Faraday in 1825, has 4 units of unsaturation. It is remarkably stable due to resonance.

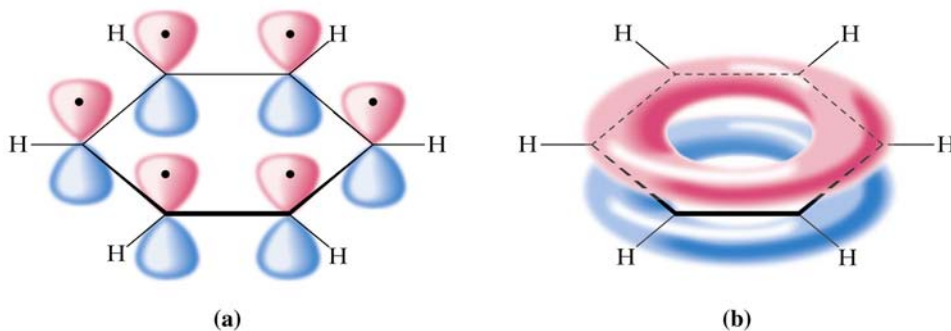
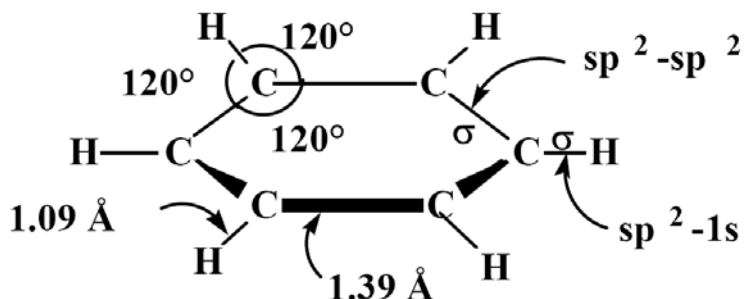


- The double bonds in the Lewis structure are so stable that benzene and compounds containing benzene rings don't undergo the typical alkene reactions, e.g.

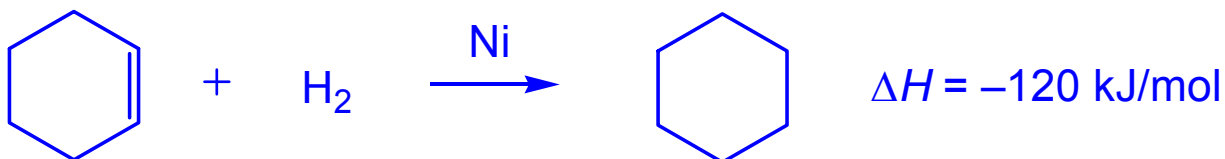


- Some of the first-known compounds containing a benzene ring had pleasant odours (e.g. benzaldehyde smells like maraschino cherries, lab #5). Thus, they are also known as **aromatic compounds**. However, many of them are toxic and carcinogenic (e.g. benzo[α]pyrene in cigarette smoke).
- In IUPAC nomenclature, benzene compounds are known as the **arenes**. Substituents with an aromatic group are named as **aryl** (phenyl) substituents and given the symbol **Ar**.

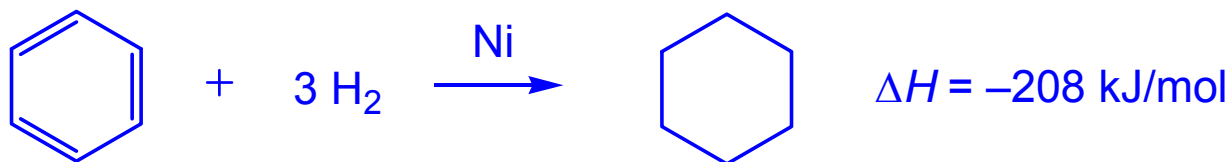
- The stability of benzene is explained by molecular orbital theory. All the p orbitals of the sp^2 -hybridized C atoms combine to form a molecular orbital which has a torus-shaped orbit (donut) on each side of the plane ring.
- All 6 C and 6 H lie in a plane in a regular hexagon, 120° .
- Each C has a p orbital containing one lone electron, and sideways overlap of the lobes of six p orbitals gives a molecular orbital with electron density above and below the ring (Fig. 9.1).



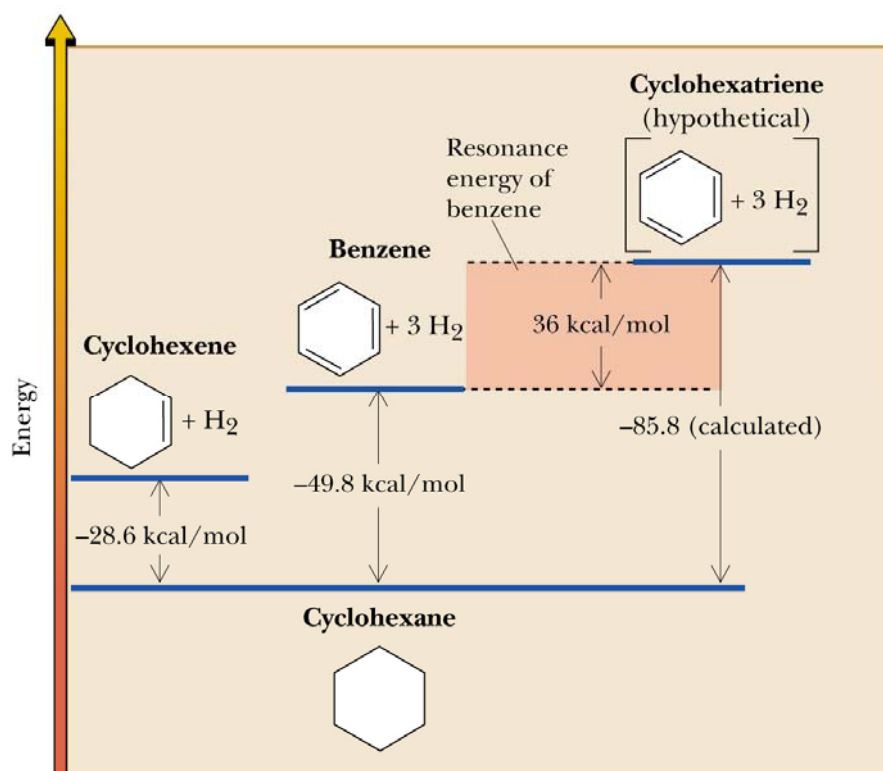
- Is there a way to estimate how much stability resonance imparts to a benzene ring? Yes, by measuring the heat (ΔH) of hydrogenation reactions of benzenes and alkenes.
- H_2 addition to one $C=C$ in cyclohexene: $\Delta H = -120 \text{ kJ/mol}$.



- So, we expect benzene to be $3 \times -120 = -360$ kJ/mol, but the measured value is $\Delta H = -208$ kJ/mol.



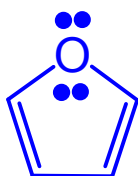
- i.e.* Benzene is $360 - 208 = 152$ kJ/mol more stable than a cyclohexane ring containing 3 C=C is expected to be.



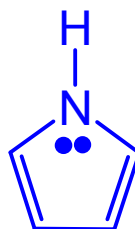
- This increased stability due to resonance is called **resonance energy**. Due to this large resonance energy, benzene does not undergo the types of electrophilic addition reactions that alkenes do. However, we'll see that benzene reacts with some reagents.

B. Aromaticity

- Resonance stabilization is a central feature, termed **aromaticity**, of all ring compounds known as aromatic compounds.
- The **three requirements** for aromaticity are:
 - A 5- or 6-membered ring that is planar;
 - One $2p$ orbital on each ring atom; and
 - Six π electrons
- Rings that contain **heteroatoms** (atoms other than C or H) can be aromatic, e.g.

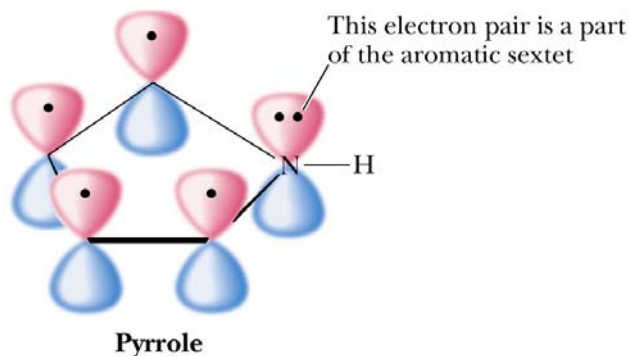
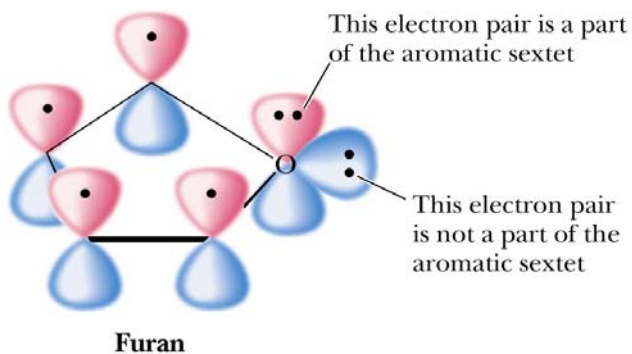


furan

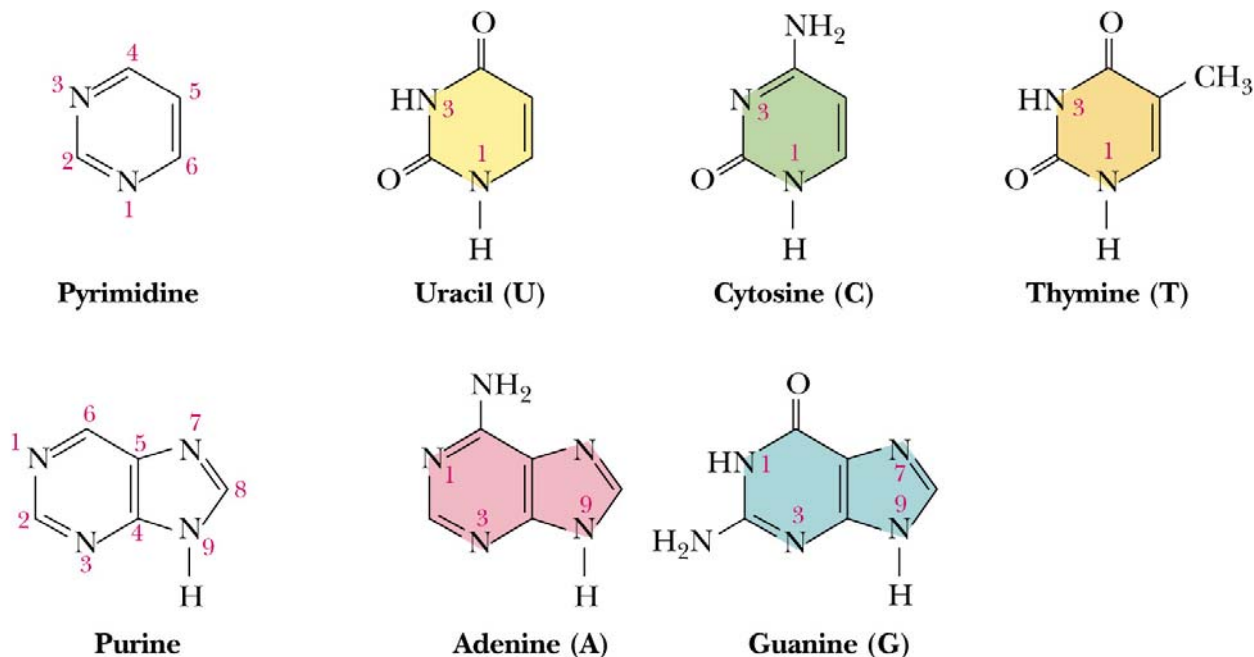


pyrrole

- The heteroatoms above are sp^2 -hybridized so that a lone pair can be placed in the remaining p orbital, which forms a molecular orbital with the p orbitals of the other atoms.

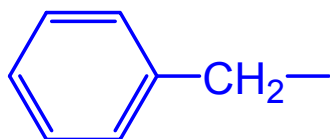


- Heterocyclic aromatic compounds are very common in bio-organic molecules, e.g. the five DNA/RNA bases (Fig 20.1).

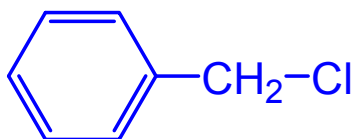


C. Nomenclature

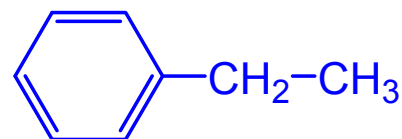
- When a benzene ring is named as a substituent in a molecule, it is called a **phenyl (Ph)**, e.g. phenylethane.
- There is also an aromatic substituent called the **benzyl (Bn)**, which is a benzene ring attached to a CH₂.
- Be careful: don't confuse phenyl with benzyl.



benzyl

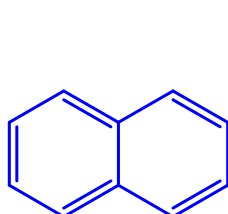


benzyl chloride

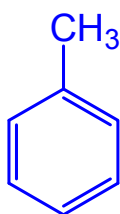


phenylethane

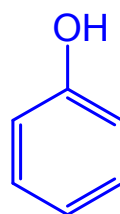
- Many aromatics have common names (know these!):



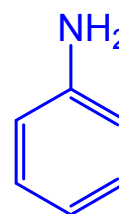
naphthalene



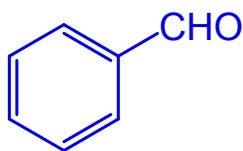
toluene



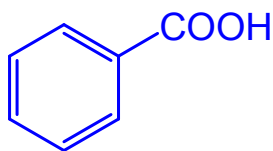
phenol



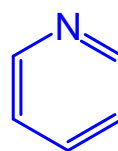
aniline



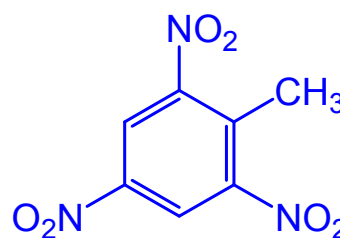
benzaldehyde



benzoic acid

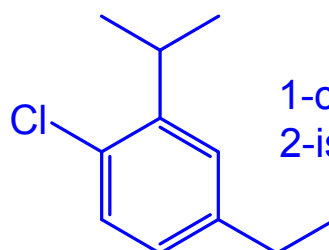


pyridine

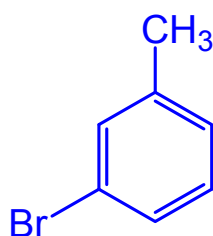
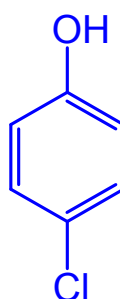


TNT

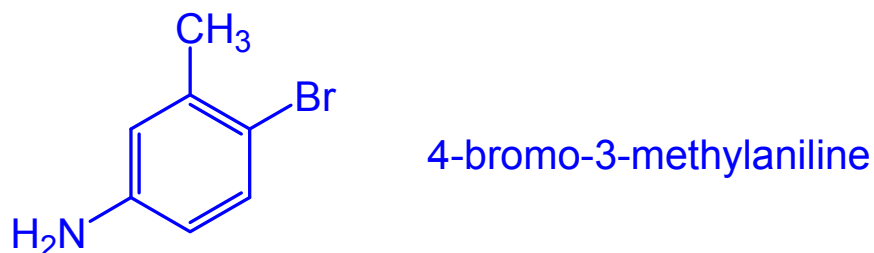
- Benzene compounds are generally named similarly to cycloalkanes.

1-chloro-4-ethyl-
2-isopropylbenzene

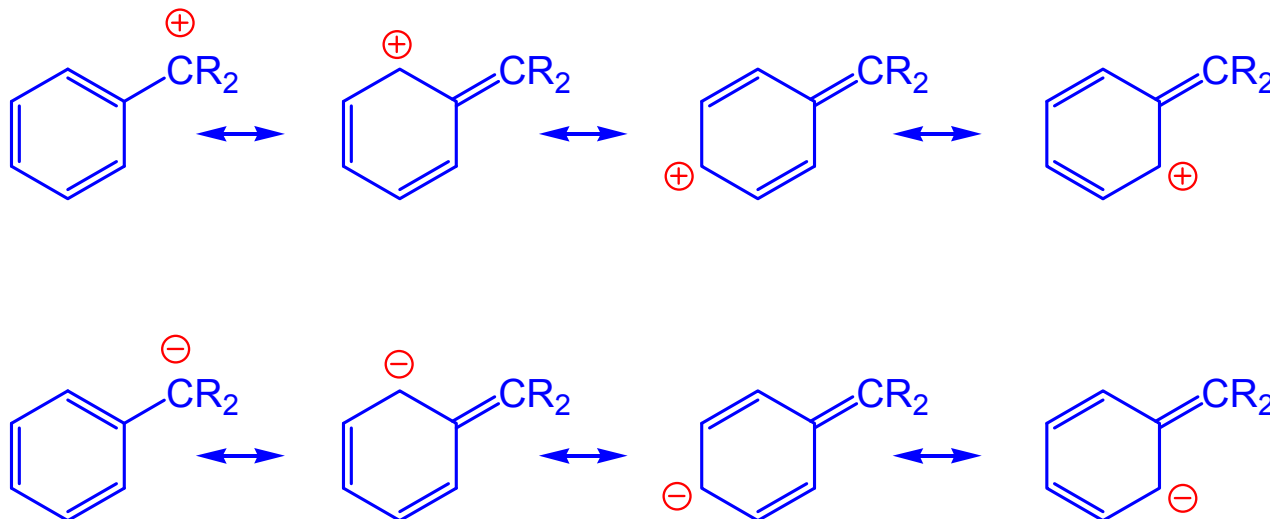
- A special naming convention is used for disubstituted benzene compounds.
 - 1,2-substituted \rightarrow *ortho* (*o*) 1,3-substituted \rightarrow *meta* (*m*)
 - 1,4-substituted \rightarrow *para* (*p*)

*m*-bromotoluene*p*-chlorophenol*o*-chloroaniline

- If aromatic compounds are named as derivatives of a commonly named benzene compound, the substituent responsible for the common name is always assigned position #1.

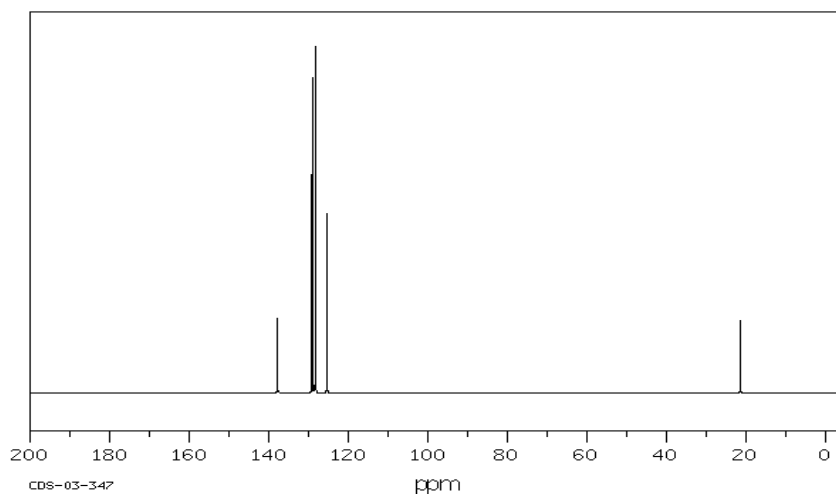
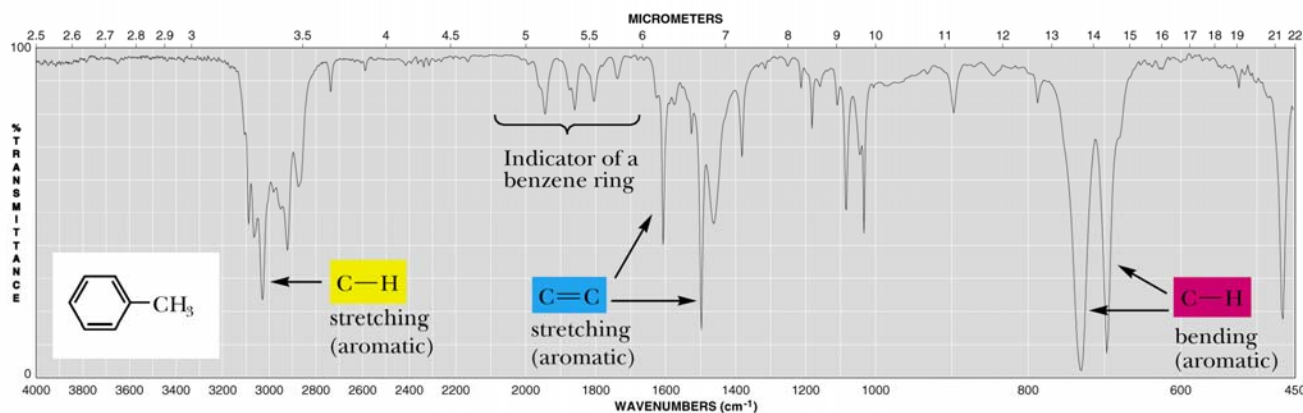


- Phenyl rings are able to stabilize adjoining cations and anions by a series of resonance structures.



D. Spectroscopy

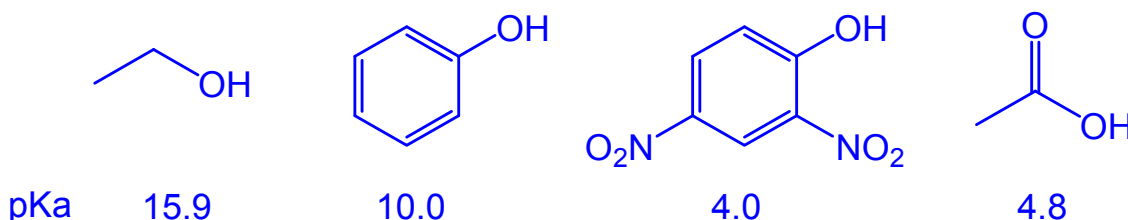
- Aromatic rings have a few characteristic, strong IR absorptions.
 - an sp^2 C–H stretch near 3030 cm^{-1}
 - several sharp peaks between $1450 - 1600\text{ cm}^{-1}$ due to C=C stretching
 - aromatic ring peaks, C–H bending $690 - 900\text{ cm}^{-1}$
 - benzene peaks $1700 - 2000\text{ cm}^{-1}$
- Carbon NMR show the expected numbers of signals.
Examples of ^{13}C -NMR and IR spectra for toluene below.



E. Reactions of Aromatic Compounds

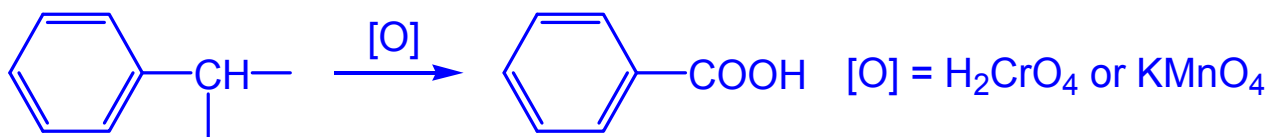
1. Acidity of phenols

- Resonance stabilization of the oxygen anion makes phenols much stronger acids than other alcohols. Added electron-withdrawing groups on the ring can make some phenols as acidic as carboxylic acids, e.g.

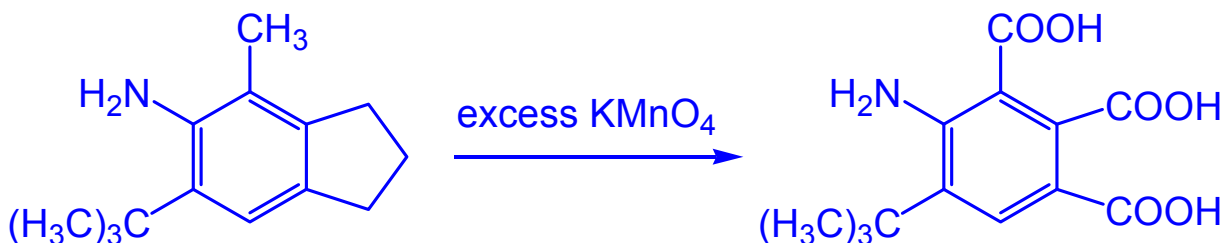


2. Oxidation of benzylic carbon atoms

- The π bonds of aromatic rings are not easily oxidized (as alkanes are), but carbon atoms directly attached to the benzene ring, termed **benzylic carbons**, are oxidized to carboxylic acids if they are *bonded to one or more H*.

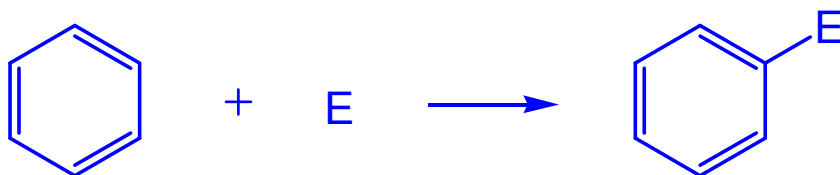


- Oxidation is not affected by other ring substituents. Remember that tertiary (with respect to the other carbons besides the ring) benzylic carbons don't oxidize.

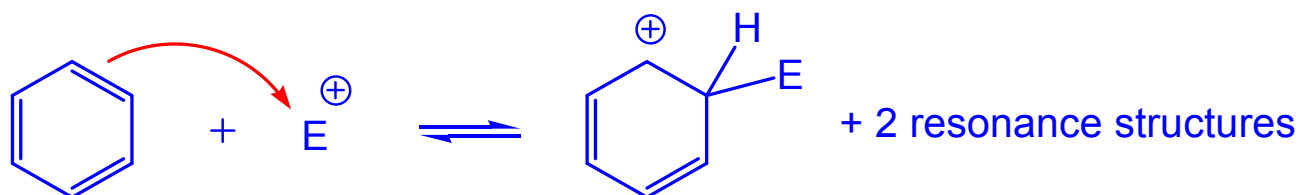


3. Electrophilic aromatic substitution (EAS)

- This is characteristic of all aromatic compounds

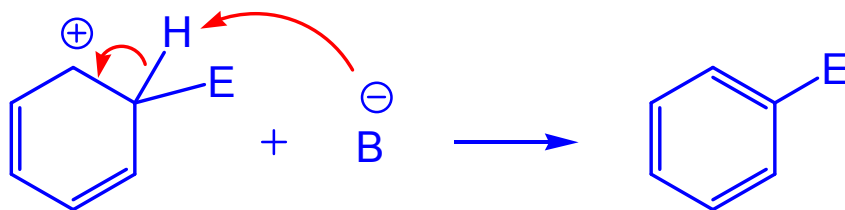


- E is a strong electrophile, usually a cation. E substitutes H in the product. It can replace two or more H, but we'll only look at monosubstitution.
- All electrophilic aromatic substitution reactions proceed by the mechanism shown below for the general electrophile E^+ .
- Step 1 is the slow, rate-determining step.** A π bond of the aromatic ring is broken and a new C–E bond is formed.



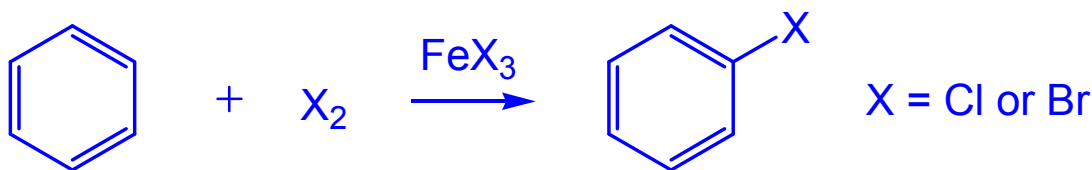
- This reversible step is endothermic because the aromaticity of the benzene ring is lost, although the carbocation is stabilized by resonance by the remaining π bonds.
- This step is very similar to the first step of the electrophilic addition mechanism of alkenes.

- In the **second, rapid exothermic step**, an anion in the reaction mixture acts as a base to remove H^+ . This regenerates a π bond and restores aromaticity.



- The two-step mechanism therefore has an electrophilic addition of E followed by the elimination of H, giving an overall substitution of H by E.
- Substitution of aromatic compounds requires much stronger E than does addition to alkenes because resonance stabilization of the ring (aromaticity) is lost in the first step.
- Specific examples are shown below.

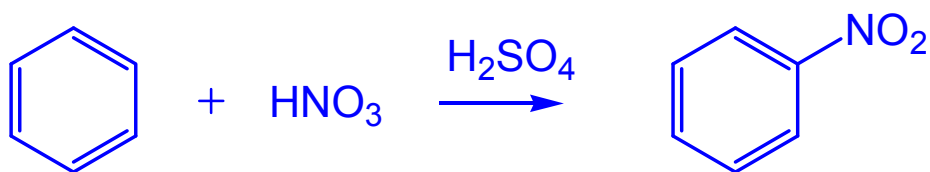
1. Chlorination and bromination



- The FeX_3 is needed to generate the strong electrophile X^+ . FeX_4^- acts as the base to remove H^+ in the 2nd step.



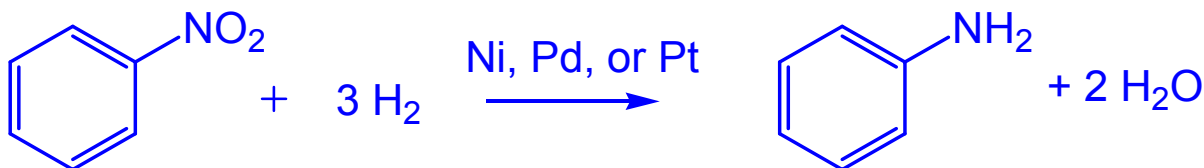
2. Nitration



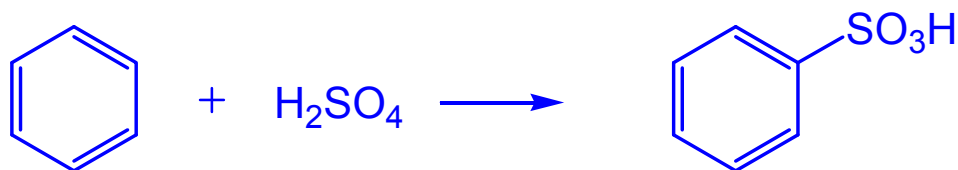
- H_2SO_4 reacts with HNO_3 to form the electrophile NO_2^+ and the base HSO_4^- .



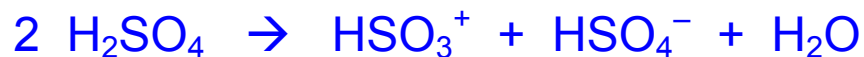
- This is the best way to add an amino group to an aromatic ring, since $-\text{NO}_2$ is easily reduced to a 1° amine.



3. Sulfonation

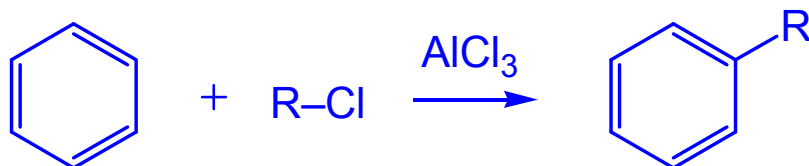


- Hot, conc. sulfuric acid generates the electrophile HSO_3^+



4. Alkylation reactions

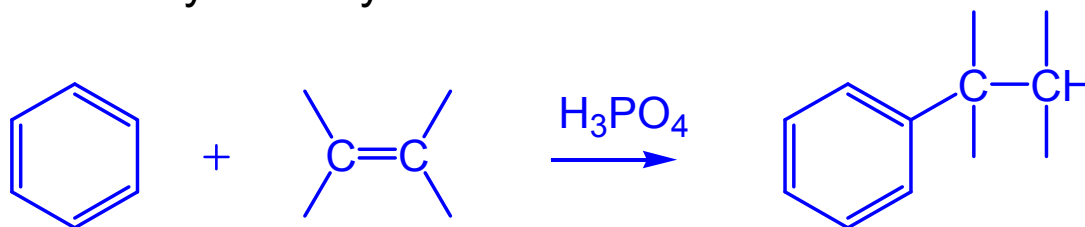
- These reactions place an R group on an aromatic ring by one of two different ways.
- A. Friedel-Crafts alkylation



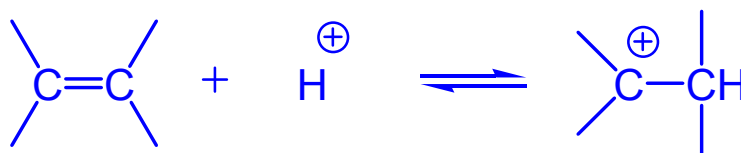
- The electrophile is a carbocation produced by the reaction of RCl and AlCl_3



- This reaction works well for most alkyl halides.
- B. Acid-catalyzed alkylation

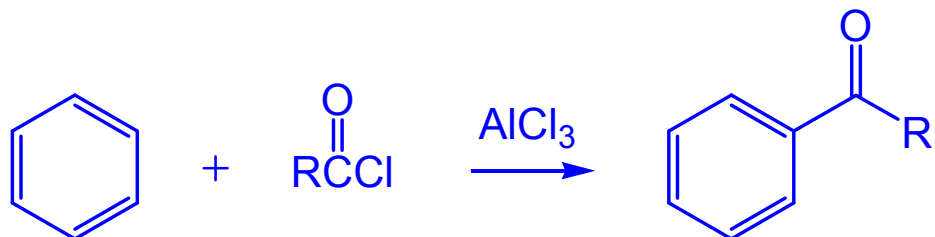


- Phosphoric acid protonates the alkene to give the most stable carbocation, which acts as the electrophile.

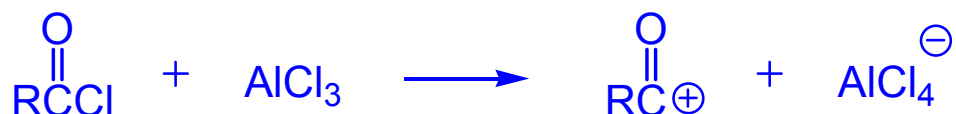


5. Friedel-Crafts acylation reactions

- This is similar to the F-C alkylation, except here, the electrophile contains a carbonyl group as the electrophile.

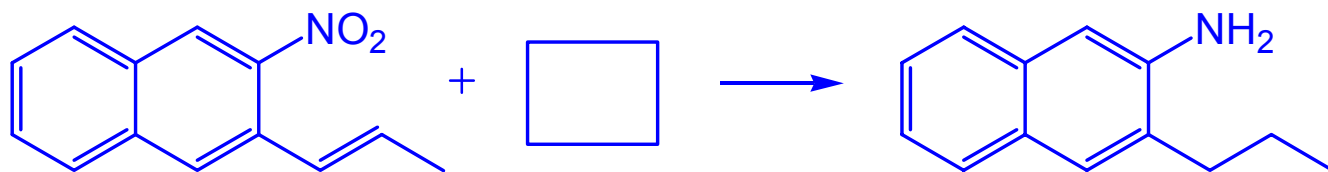
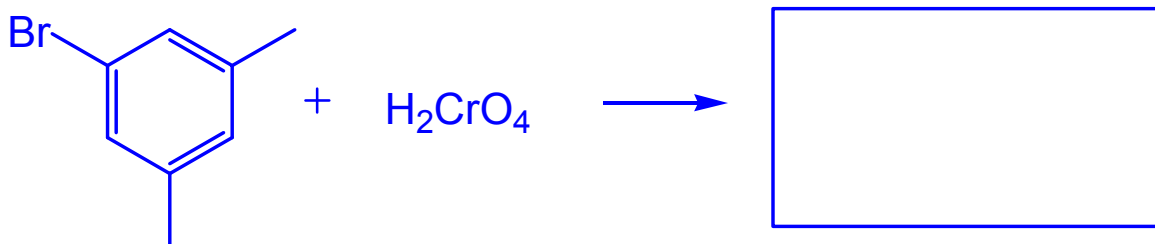


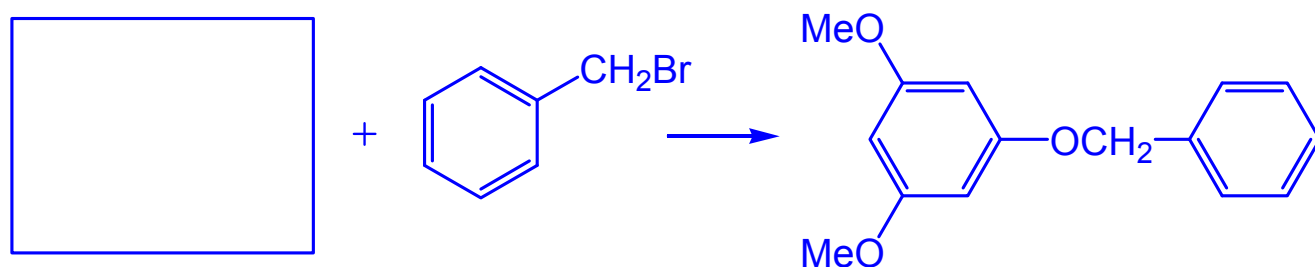
- As before, AlCl_3 reacts to form a cationic species



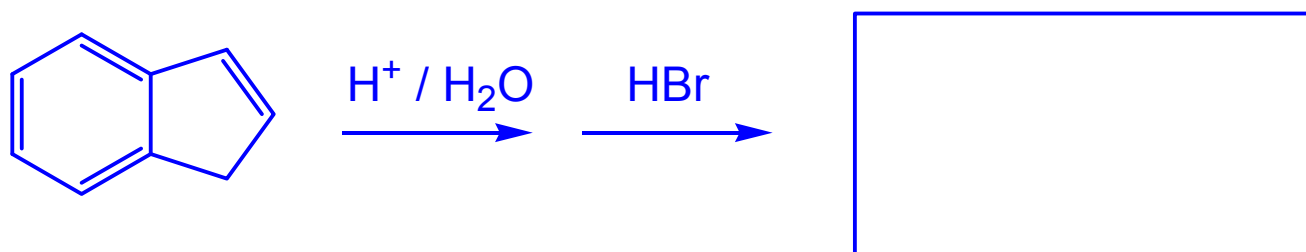
F. Predicting Products or Reactants

- You should be able to supply the needed reagents, the products, as well as any catalyst or co-reagent needed for a specified reaction.

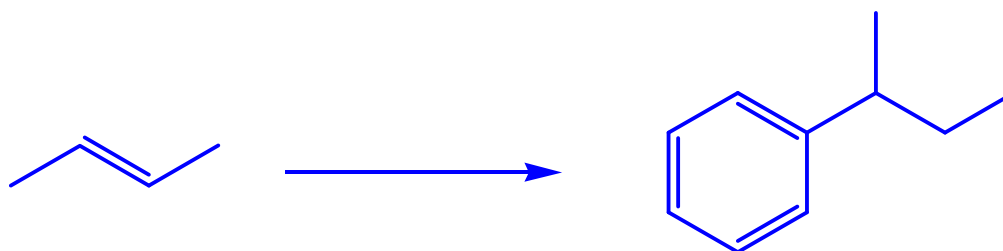




- For questions like the above, it is important that you look at the reactive sites. Don't let the unreactive parts distract you... focus on the functional groups.
- You should also be able to predict the product of a sequence of reactions.

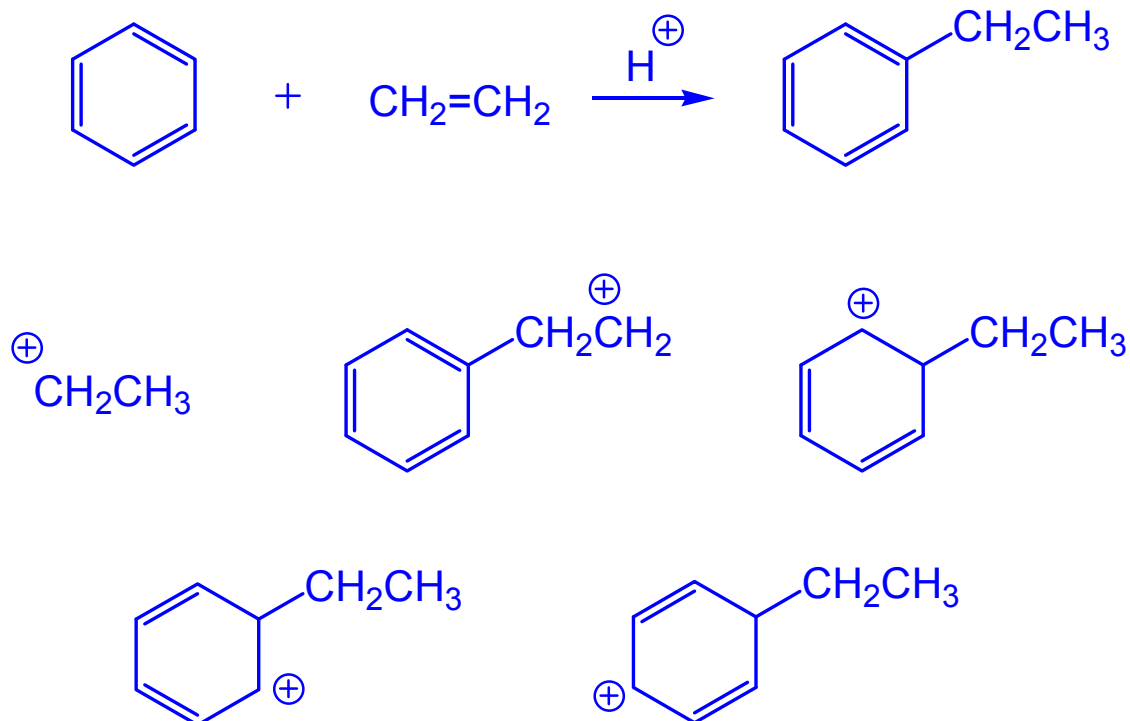


- The question that relies most heavily on your ability to recall reactions is a synthesis question, where you propose a sequence of reactions that will give a specified product.

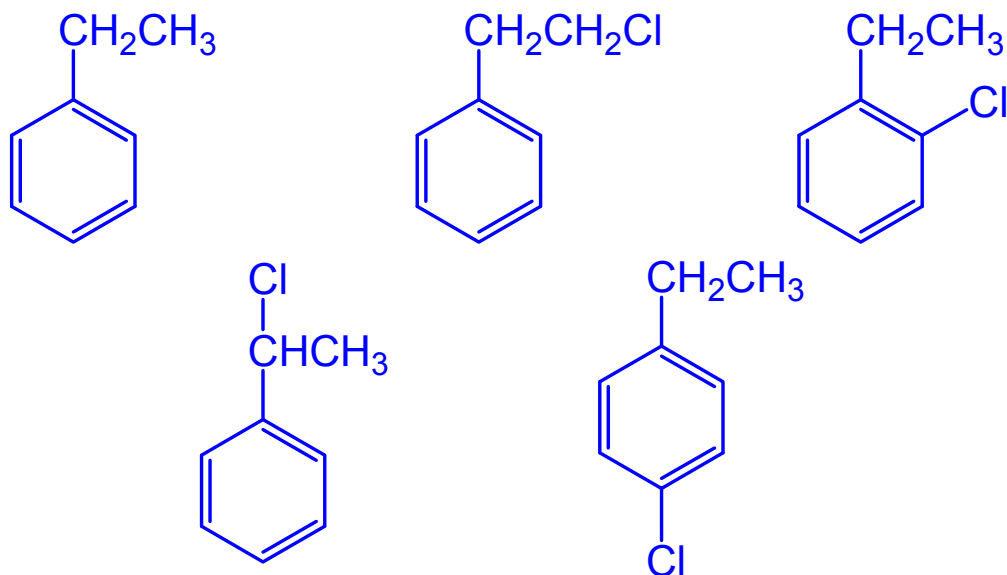


- Pages covered: Chapter 9, p. 235 – 254, 262 – 266.
- Problems: 11, 15, 19, 20, 29, 32, 33, 35 a/c, 36 a/b/d, 39, 46, 47, 50.
- 2005: 28 – 30; 2006: 26 – 29; 2007: 26 – 28; 2008: 26 – 29

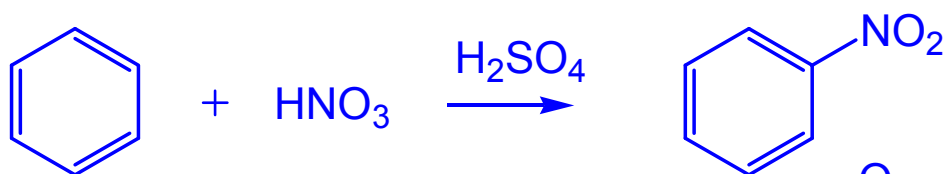
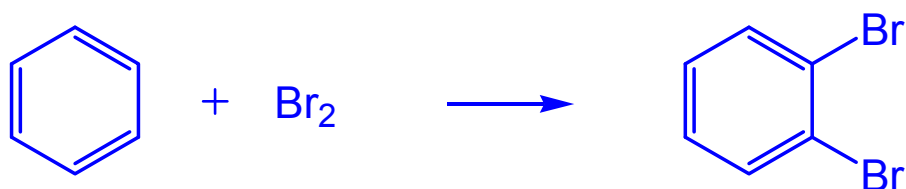
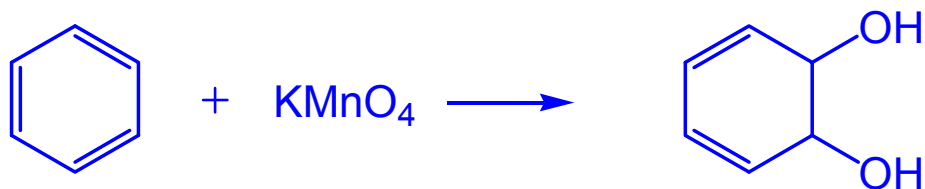
- Past test questions: In the acid-catalyzed ethylation of benzene, which one of the following is NOT part of the accepted mechanism?



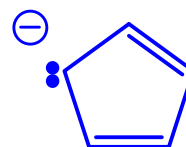
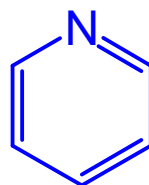
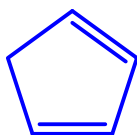
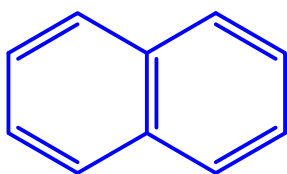
- Which one of the following molecules has eight different absorption signals in its ^{13}C -NMR spectrum?



- Which of these reactions proceed as written? (more than 1)



- MCAT: Which of the following structures is NOT aromatic?



- MCAT: What is the correct name for this molecule?



- *para*-nitrotoluene
 - *ortho*-nitrotoluene
 - *para*-toluene
 - *meta*-nitrotoluene
- MCAT: Why does benzene undergo substitution reactions rather than addition reactions?
 - Benzene does not have a double bond
 - If benzene underwent an addition reaction, the aromaticity of the ring would be disrupted
 - When benzene undergoes a substitution reaction, the aromaticity is disrupted
 - Benzene is an alkene