3.10 Benzene: Aromatic Hydrocarbons / Arenes

There are two major classes of organic chemicals:
- **Aliphatic**: straight or branched chain organic substances
- **Aromatic or arene**: includes one or more ring of six carbon atoms with delocalised bonding.

**Benzene’s Structure**
The simplest arene is benzene. It has the molecular formula C₆H₆. Its basic structure is six C atoms in a hexagonal ring, with one H atom bonded to each C atom. Each C atom is bonded to two other C atoms and one H atom by single covalent σ-bonds. This leaves one unused electron on each C atom in a p orbital, perpendicular to the plane of the ring. The Six p electrons are delocalised in a ring structure above and below the plane of carbon atoms.

The six electrons in the pi bonds are delocalised and spread out over the whole ring. Delocalised means not attached to a particular atom.

**Using Enthalpies of Hydrogenation to show Thermodynamic Stability**

- Cyclohexene + H₂ → Cyclohexane
  \[ \Delta H = -120 \text{ kJ/mol} \]
- Non delocalised structure
  \[ \Delta H = -360 \text{ kJ/mol} \]
- Delocalised structure
  \[ \Delta H = -208 \text{ kJ/mol} \]

Theoretically because there are 3 double bonds in the theoretical cyclohexa-1,3,5-triene one might expect the amount of energy to be 3 times as much as cyclohexene.

However, in actual benzene the amount of energy is less. The 6 pi electrons are delocalised and not arranged in 3 double bonds.

The increase in stability connected to delocalisation is called the **delocalisation energy**.

In cyclohexa-1,3-diene, there would be some delocalisation and extra stability as the pi electrons are close together and so overlap. The hydrogenation value would be less negative than -240 kJ/mol (showing more stable).

In cyclohexa-1,4-diene, there would not be delocalisation as the pi electrons are too far apart and so don’t overlap. The hydrogenation value would be -240 kJ/mol.

Benzene is a planar molecule. The evidence suggests all the C-C bonds are the same and have a length and bond energy between a C-C single and C=C double bond.

In formulae we draw a circle to show this delocalised system.

The H-C-C bond angle is 120° in Benzene.
Naming aromatic molecules

Naming aromatic compounds can be complicated. The simplest molecules are derivatives of benzene and have benzene at the root of the name.

Methylbenzene  ethylbenzene  chlorobenzene  bromobenzene  nitrobenzene  benzenecarboxylic acid  benzaldehyde

If two or more substituents are present on the benzene ring, their positions must be indicated by the use of numbers. This should be done to give the lowest possible numbers to the substituents. When two or more different substituents are present, they are listed in alphabetical order and di, tri prefixes should be used.

1,3-dimethylbenzene  1-chloro 4-methylbenzene  4-hydroxybenzenecarboxylic acid  2,4,6-trinitromethylbenzene

In other molecules the benzene ring can be regarded as a substituent side group on another molecule, like alkyl groups are. The C₆H₅- group is known as the phenyl group.

phenylamine  phenylethene  2-phenylbutane  phenylethanone  phenylethanoate

1-phenylpropane-1,2-diol  3-phenylpropanal

Reactions of Benzene
Benzene does not generally undergo addition reactions because these would involve breaking up the delocalised system. Most of Benzene's reactions involve substituting one H for another atom or group of atoms. Benzene has a high electron density and so attracts electrophiles. It reactions are usually **electrophilic substitutions**.

Toxicity of Benzene
Benzene is a carcinogen (cancers causing molecule) and is banned for use in schools. Methylbenzene is less toxic and also reacts more readily than benzene as the methyl side group releases electrons into the delocalised system making it more attractive to electrophiles.
Nitration of Benzene

**Change in functional group:** benzene → nitrobenzene

**Reagents:** conc nitric acid in the presence of concentrated sulphuric acid (catalyst)

**Mechanism:** Electrophilic Substitution

**Electrophile:** NO$_2^+$

**Equation for Formation of electrophile: (Learn!)**

\[ \text{HNO}_3 + 2\text{H}_2\text{SO}_4 \rightarrow \text{NO}_2^+ + 2\text{HSO}_4^- + \text{H}_3\text{O}^+ \]

This is an acid base reaction. The HNO$_3$ acts as a base.

**Overall Equation for reaction**

\[ \text{-} + \text{NO}_2^+ \rightarrow \text{NO}_2^- + \text{H}^+ \]

**Mechanism**

The horseshoe shape of the intermediate must not extend beyond C’s 2 to 6

The H$^+$ ion rejoins with the HSO$_4^-$ to reform H$_2$SO$_4$ catalyst.

This reaction is done at 60°C. On using higher temperatures a second nitro group can be substituted.

**Friedel Crafts Acylation**

**Change in functional group:** benzene → phenyl ketone

**Reagents:** acyl chloride in the presence of anhydrous aluminium chloride catalyst

**Conditions:** heat under reflux (50°C)

**Mechanism:** Electrophilic Substitution

**Equation for Formation of the electrophile.**

\[ \text{AlCl}_3 + \text{CH}_3\text{COCl} \rightarrow \text{CH}_3\text{CO}^+ \text{AlCl}_4^- \]

**Overall Equation for reaction**

\[ \text{CH}_3\text{CO}^+ \text{AlCl}_4^- + \text{-} \rightarrow \text{CH}_3\text{CO} \text{C}_{\text{H}_3} + \text{AlCl}_3 + \text{HCl} \]

**Mechanism**

The H$^+$ ion reacts with the AlCl$_4^-$ to reform AlCl$_3$ catalyst and HCl.

These are important reactions in organic synthesis because they introduce a reactive functional group on to the benzene ring.

**Importance of this reaction**

Nitration of benzene and other arenes is an important step in synthesising useful compounds e.g. explosive manufacture (like TNT, trinitrotoluene/2,4,6-trinitromethylbenzene) and formation of amines from which dyestuffs are manufactured. (The reaction for this is covered in the amines section.)
Reducing a Nitroarene to aromatic amines

The nitro group on an arene can be reduced an amine group as follows

| Reagent: Sn and HCl or Fe and HCl |
| Conditions: Heating |
| Mechanism: reduction |

\[
\text{NO}_2^- + 6\text{[H]} + 2\text{H}_2\text{O} \rightarrow \text{NH}_2^- + 2\text{H}_2\text{O}
\]

This reduction reaction can also be done with catalytic hydrogenation (H\textsubscript{2} using a Ni catalyst)

As the reaction is carried out in HCl, the ionic salt C\textsubscript{6}H\textsubscript{5}NH\textsubscript{3}+Cl\textsuperscript{-} will be formed, which is soluble in water. Reacting this salt with NaOH will give the insoluble phenylamine.

Effect of delocalisation on side groups with lone pairs

If a –OH group, a Cl atom or an NH\textsubscript{2} group is directly attached to a benzene ring the delocalisation in the benzene ring will extend to include the lone pairs on the N, O and Cl. This changes the properties and reactions of the side group.

The C-Cl bond is made stronger. Typical halogenoalkane substitution and elimination reactions do not occur. Also the electron rich benzene ring will repel nucleophiles.

Delocalisation makes the C-O bond stronger and the O-H bond weaker. Phenol does not act like an alcohol- it is more acidic and does not oxidise.

Less basic than aliphatic amines as lone pair is delocalised and less available for accepting a proton.
Aromatic Synthetic Routes

Remember that many questions about aromatic compounds will actually be about normal aliphatic reactions of the side chains and not about the benzene ring.