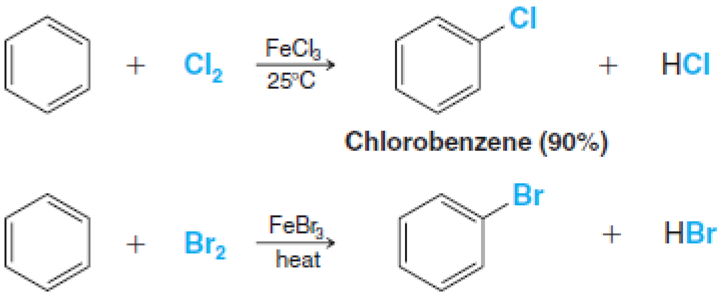
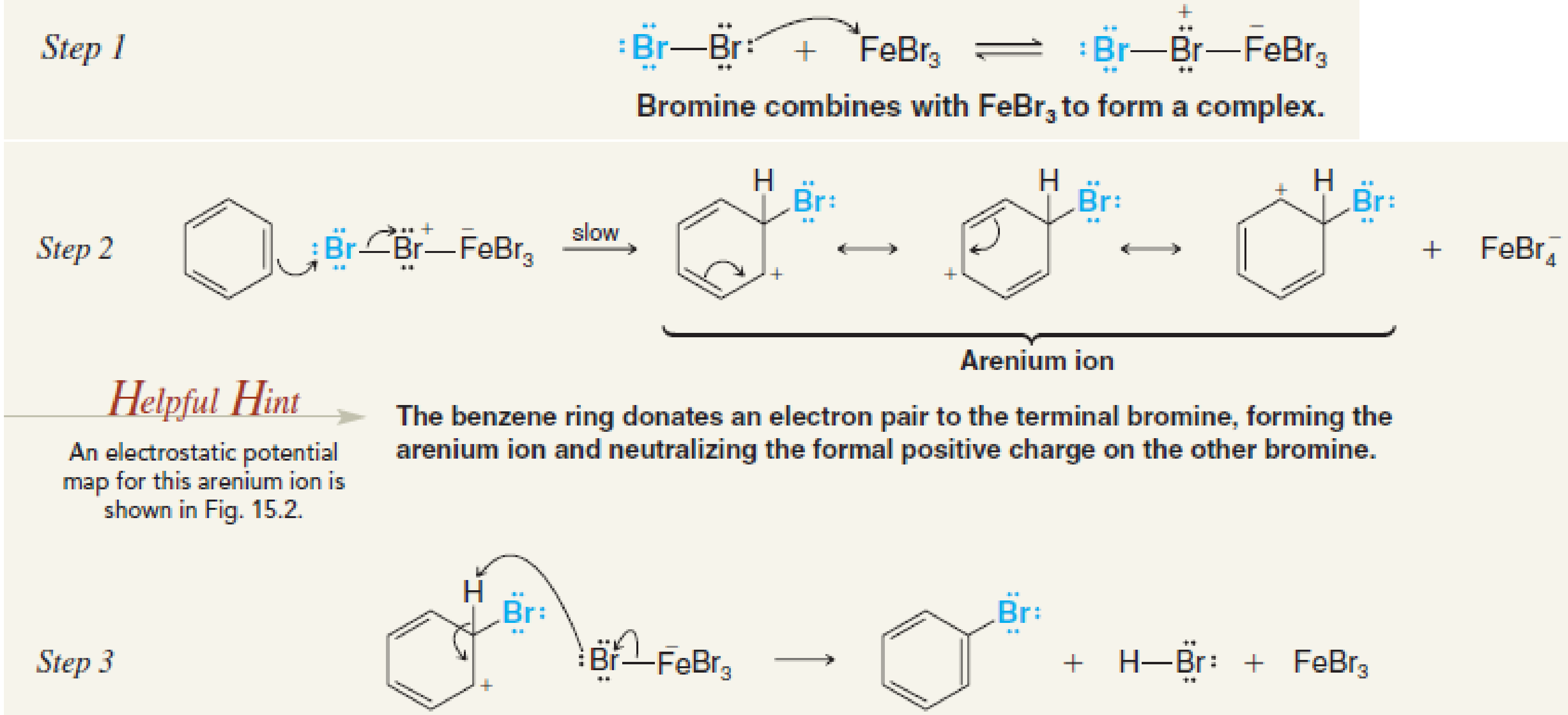
Halogenation of Benzene:



Chlorobenzene (90%)

Bromobenzene (75%)

The purpose of the Lewis acid is to make the halogen a stronger electrophile.



Bromine combines with $FeBr_3$ to form a complex.

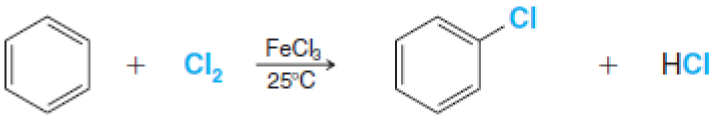
Arenium ion

The benzene ring donates an electron pair to the terminal bromine, forming the arenium ion and neutralizing the formal positive charge on the other bromine.

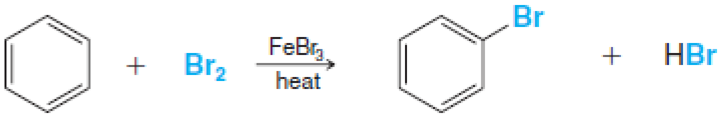
An electrostatic potential map for this arenium ion is shown in Fig. 15.2.

A proton is removed from the arenium ion to form bromobenzene and regenerate the catalyst.

Halogenation of Benzene:

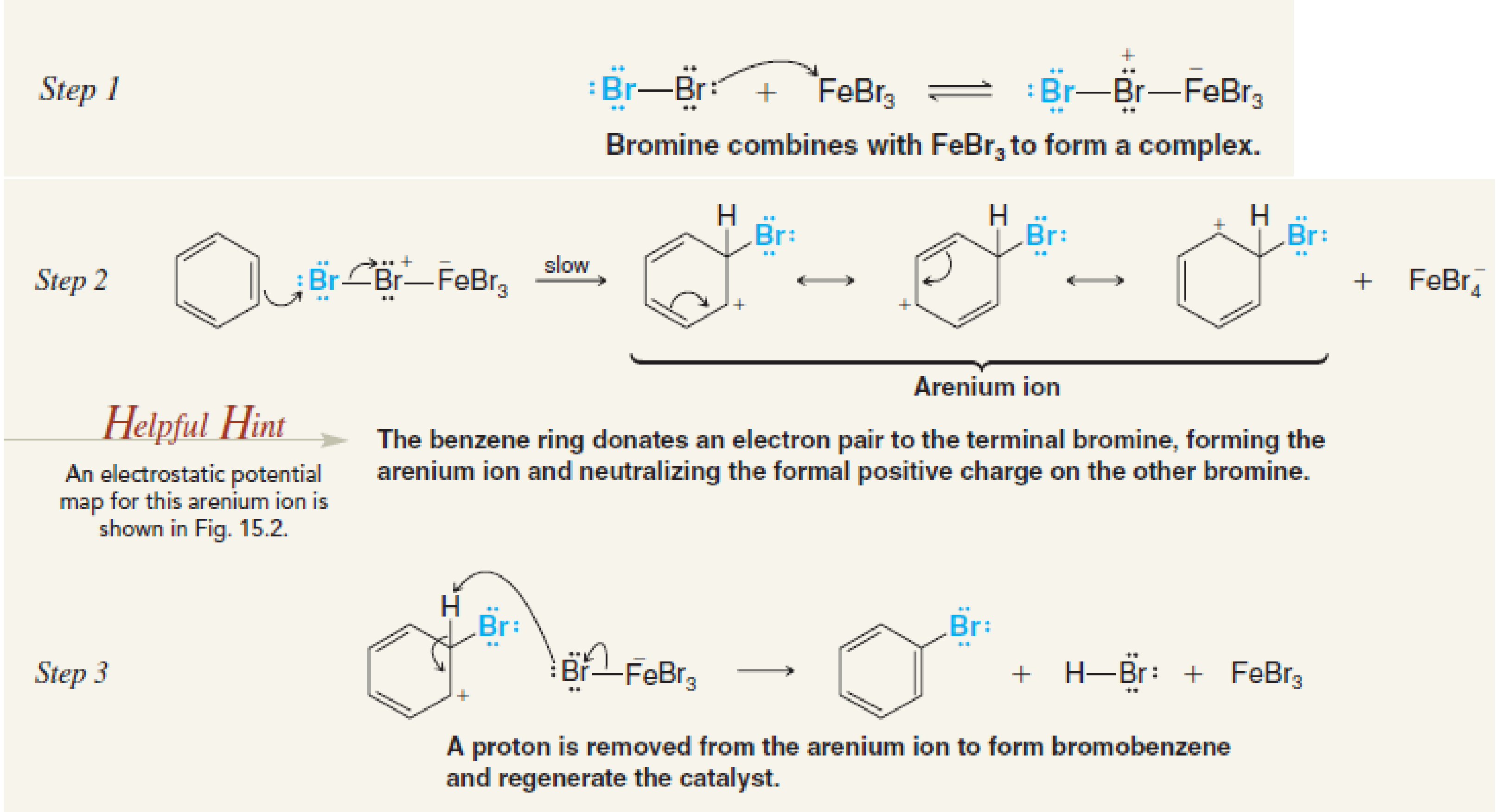


Chlorobenzene (90%)



Bromobenzene (75%)

The purpose of the Lewis acid is to make the halogen a stronger electrophile.



Bromine combines with $FeBr_3$ to form a complex.

Arenium ion

Helpful Hint

An electrostatic potential map for this arenium ion is shown in Fig. 15.2.

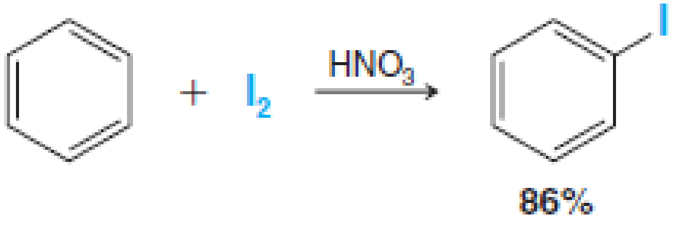
The benzene ring donates an electron pair to the terminal bromine, forming the arenium ion and neutralizing the formal positive charge on the other bromine.

A proton is removed from the arenium ion to form bromobenzene and regenerate the catalyst.

The mechanism of the **chlorination** of benzene in the presence of *ferric chloride* is analogous to the one for bromination.

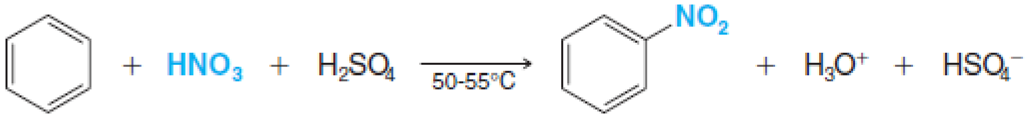
Fluorine reacts so rapidly with benzene that aromatic fluorination requires special conditions and special types of apparatus. Even then, it is difficult to limit the reaction to monofluorination. Fluorobenzene can be made, however, by an indirect method.

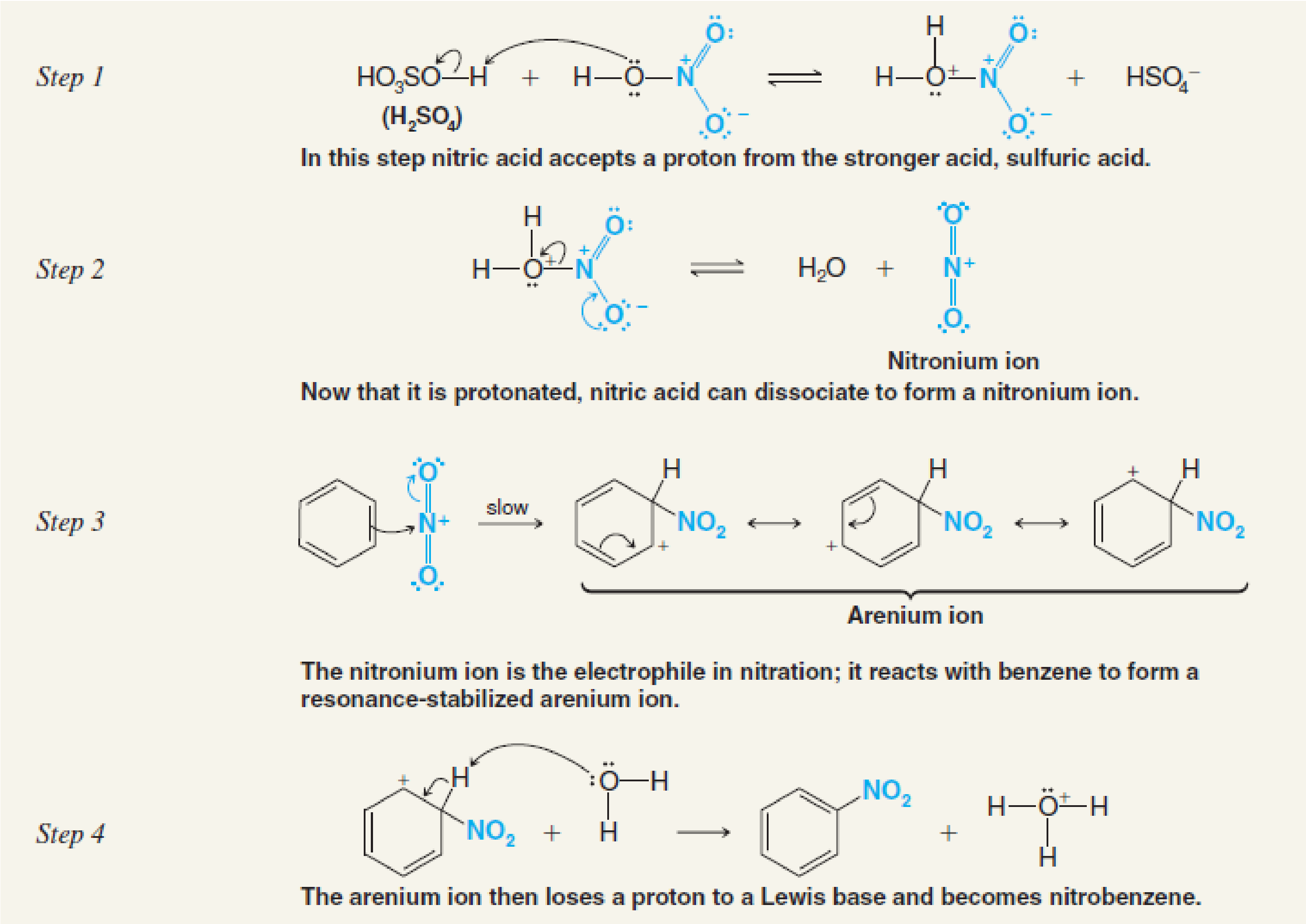
Iodine, on the other hand, is so unreactive that a special technique has to be used to effect direct iodination; the reaction has to be carried out in the presence of an oxidizing agent such as nitric acid.



Nitration of Benzene:

Benzene undergoes nitration on reaction with a **mixture** of concentrated nitric acid and concentrated sulfuric acid.





Step 1

In this step nitric acid accepts a proton from the stronger acid, sulfuric acid.

Step 2

Now that it is protonated, nitric acid can dissociate to form a nitronium ion.

Step 3

The nitronium ion is the electrophile in nitration; it reacts with benzene to form a resonance-stabilized arenium ion.

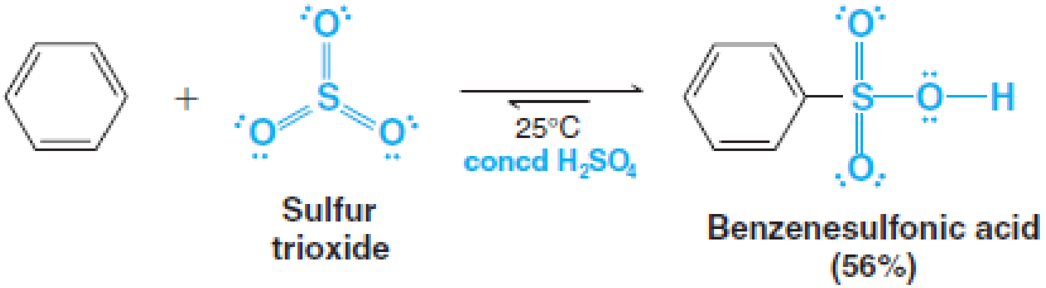
Step 4

The arenium ion then loses a proton to a Lewis base and becomes nitrobenzene.

Sulfonation of Benzene:

Benzene reacts with fuming sulfuric acid at room temperature to produce benzenesulfonic acid. Fuming sulfuric acid is sulfuric acid that contains added sulfur trioxide (SO_3).

Sulfonation also takes place in concentrated sulfuric acid alone, but more slowly. Under either condition, the electrophile appears to be sulfur trioxide.



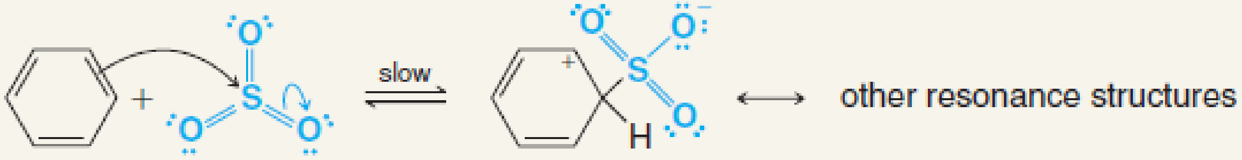
In concentrated sulfuric acid, sulfur trioxide is produced in an equilibrium in which H_2SO_4 acts as both an acid and a base (see step 1 of the following mechanism).

Step 1

$$2\,H_2SO_4 \rightleftharpoons SO_3 + H_3O^+ + HSO_4^-$$

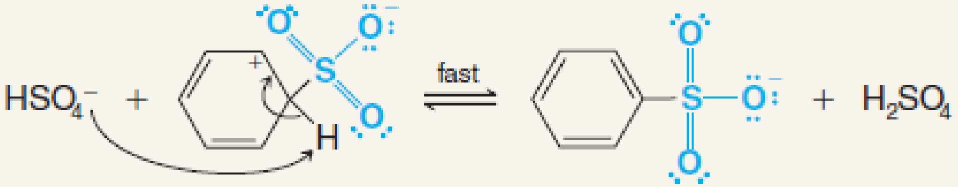
This equilibrium produces SO_3 in concentrated H_2SO_4.

Step 2



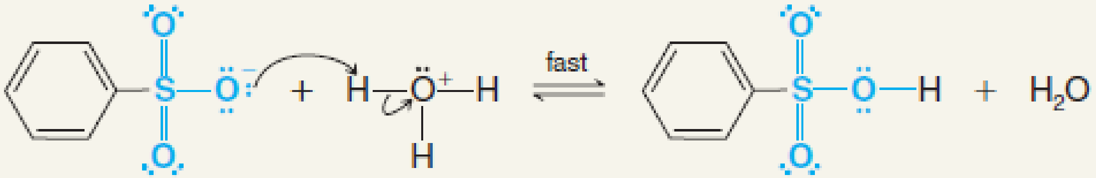
SO_3 is the electrophile that reacts with benzene to form an arenium ion.

Step 3



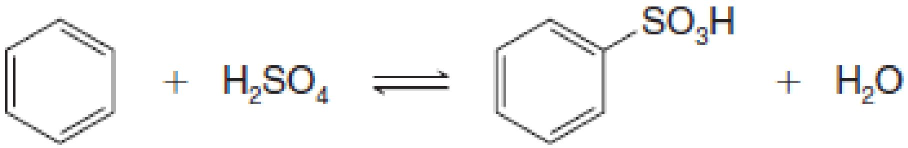
A proton is removed from the arenium ion to form the benzenesulfonate ion.

Step 4



The benzenesulfonate ion accepts a proton to become benzenesulfonic acid.

All of the steps in sulfonation are equilibria, which means that the overall reaction is **reversible**. The position of equilibrium can be influenced by the conditions we employ.



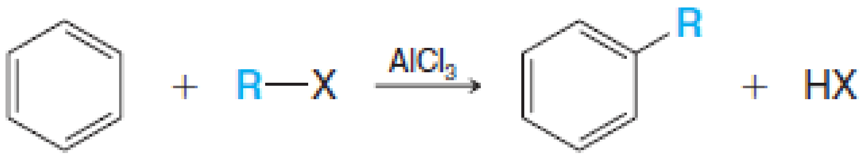
If we want to sulfonate the ring (install a sulfonic acid group), we use concentrated sulfuric acid or—better yet—fuming sulfuric acid. Under these conditions the position of equilibrium lies appreciably to the right, and we obtain benzenesulfonic acid in good yield.

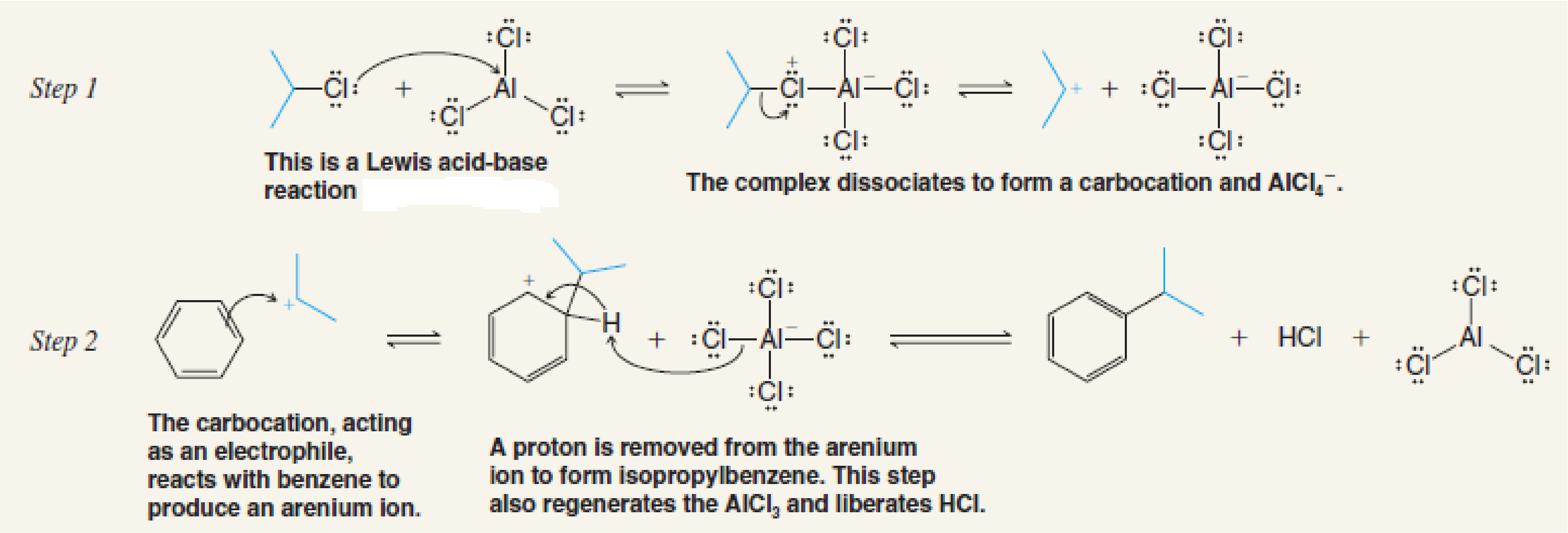
If we want to desulfonate the ring (**remove** a sulfonic acid group), we employ dilute sulfuric acid and usually pass steam through the mixture. Under these conditions—with a high concentration of water—the equilibrium lies appreciably to the left and desulfonation occurs.

We sometimes install a sulfonate group **as a protecting group**, to temporarily block its position from electrophilic aromatic substitution, or **as a directing group, to influence the position** of another substitution relative to it.

When it is no longer needed we remove the sulfonate group.

Friedel–Crafts Alkylation





This is a Lewis acid-base reaction

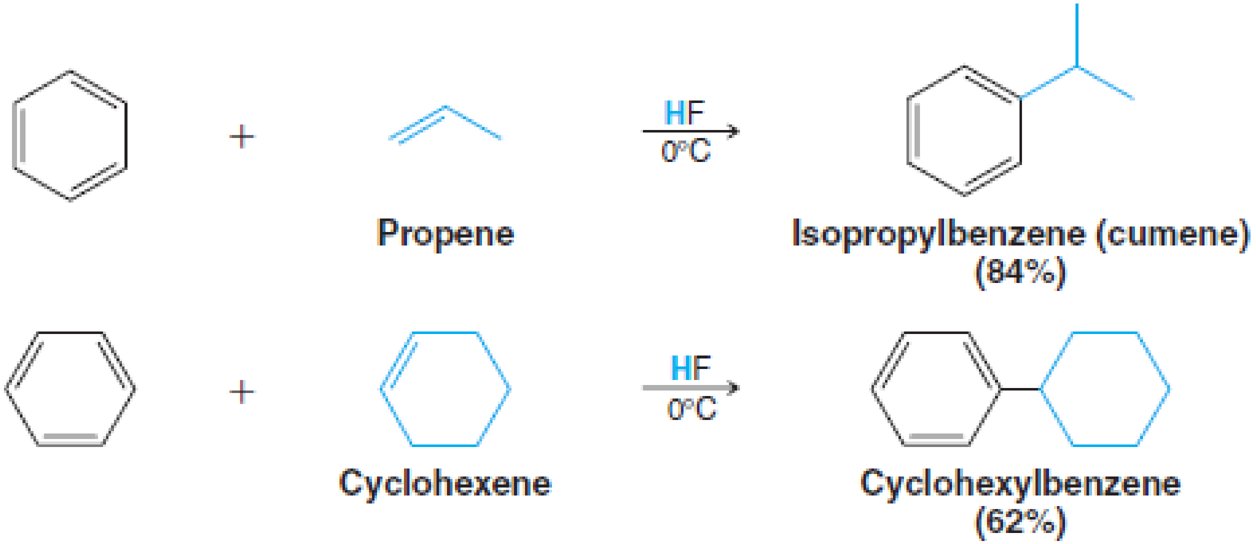
The complex dissociates to form a carbocation and $AlCl_4^-$.

The carbocation, acting as an electrophile, reacts with benzene to produce an arenium ion.

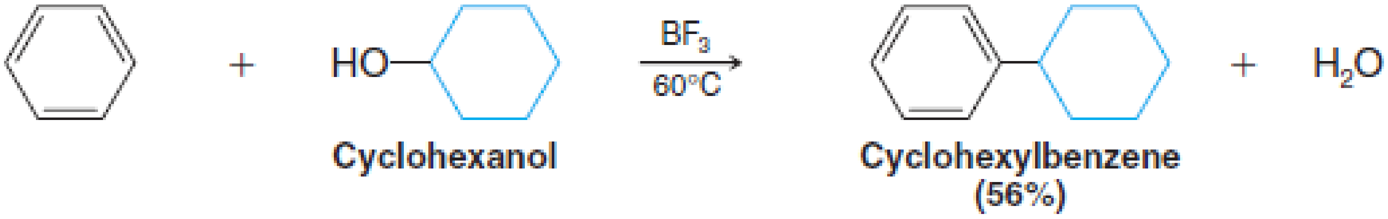
A proton is removed from the arenium ion to form isopropylbenzene. This step also regenerates the $AlCl_3$ and liberates HCl.

Friedel–Crafts alkylations are not restricted to the use of alkyl halides and aluminum chloride. Other pairs of reagents that form carbocations (or species like carbocations) may be used in Friedel–Crafts alkylations as well.

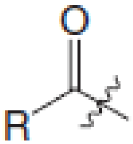
These possibilities include the use of a mixture of an alkene and an acid:

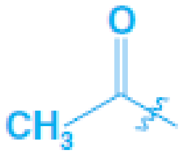


A mixture of an alcohol and an acid may also be used:

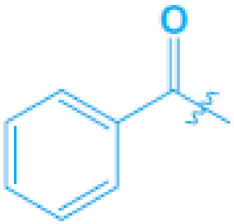


Friedel–Crafts Acylation

The  group is called an **acyl group**, and a reaction whereby an acyl group is introduced into a compound is called an **acylation** reaction.

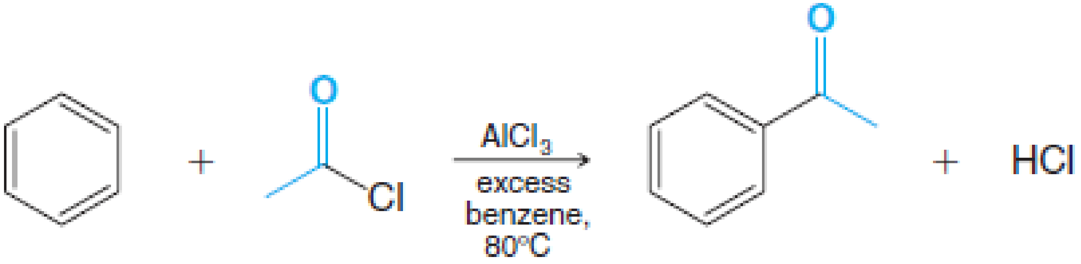


Acetyl group (ethanoyl group)

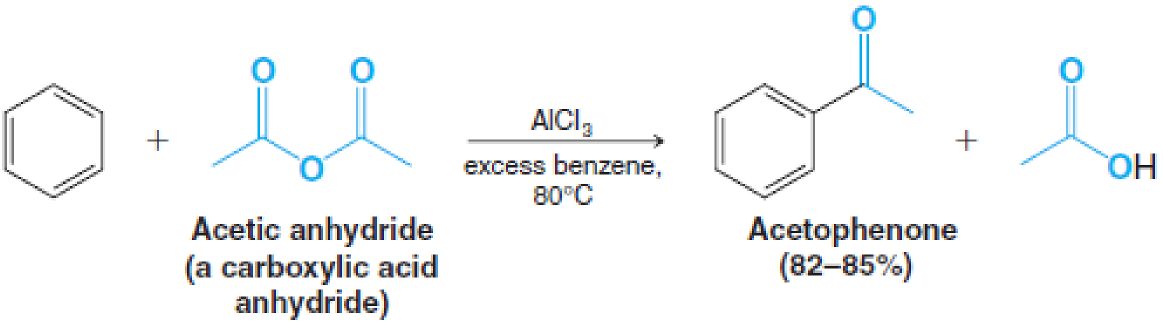


Benzoyl group

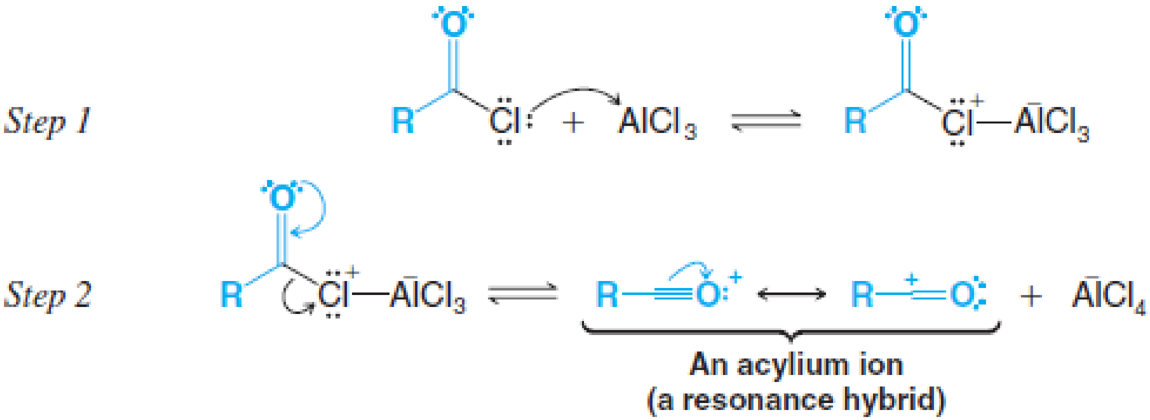
The **Friedel–Crafts acylation** reaction is often carried out by treating the aromatic compound with an **acyl halide** (often an acyl chloride). Unless the aromatic compound is one that is highly reactive, the reaction requires the addition of at least one equivalent of a Lewis acid (such as $AlCl_3$) as well. The product of the reaction is an aryl ketone:



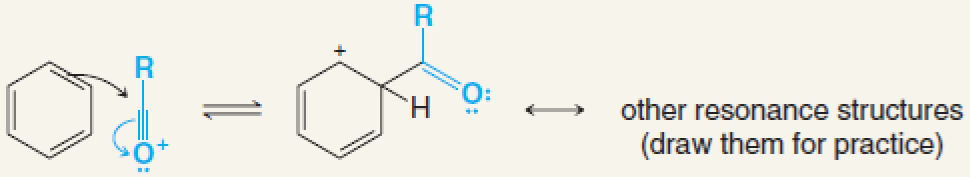
Friedel–Crafts acylations can also be carried out using carboxylic acid anhydrides.



In most Friedel–Crafts acylations the electrophile appears to be an **acylium ion** formed from an acyl halide in the following way:

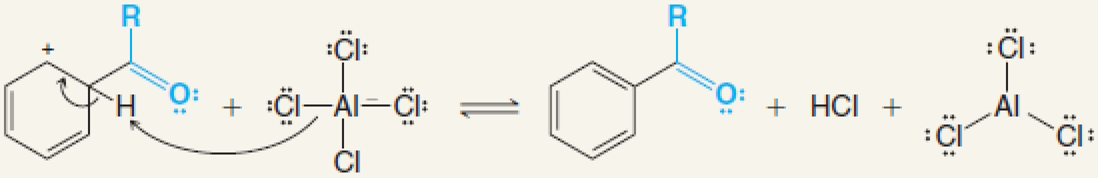


Step 3



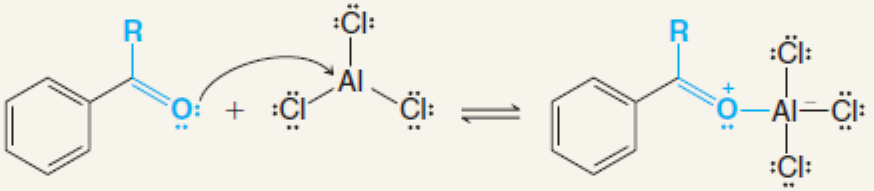
The acylium ion, acting as an electrophile, reacts with benzene to form the arenium ion.

Step 4



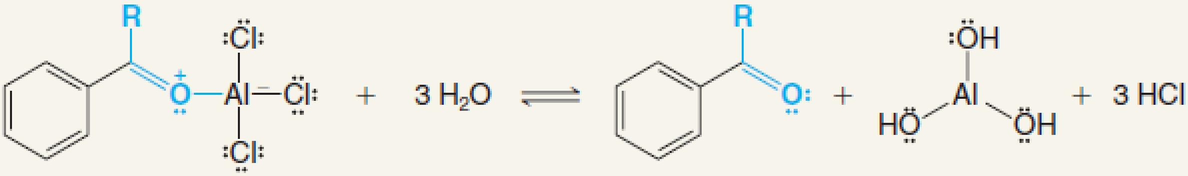
A proton is removed from the arenium ion, forming the aryl ketone.

Step 5



The ketone, acting as a Lewis base, reacts with aluminum chloride (a Lewis acid) to form a complex.

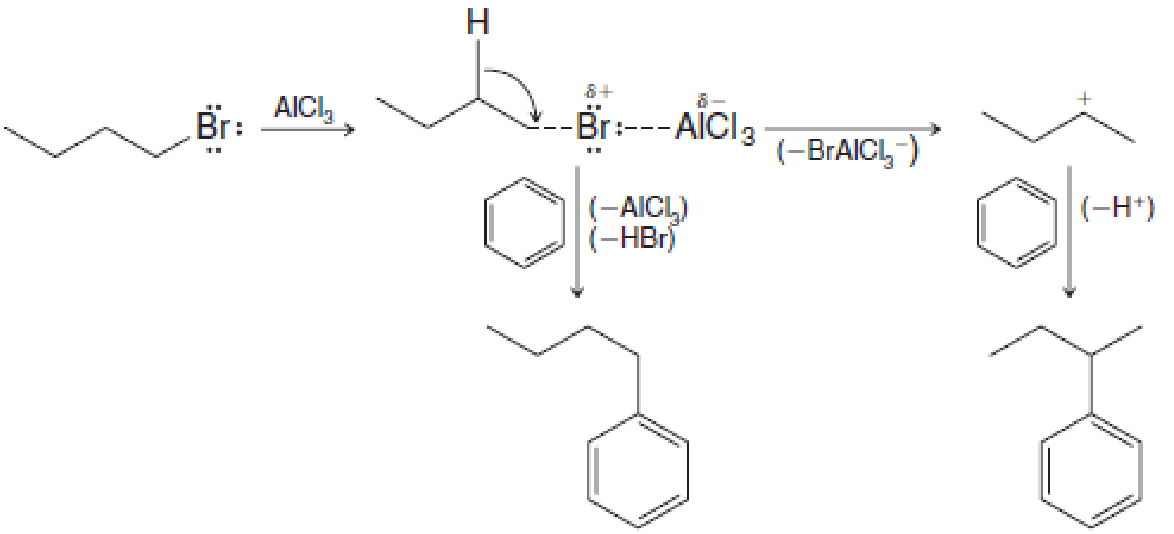
Step 6



Treating the complex with water liberates the ketone and hydrolyzes the Lewis acid.

Limitations of Friedel–Crafts Reactions

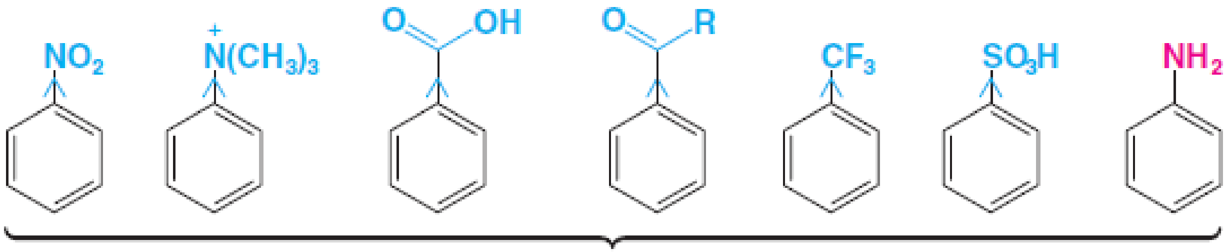
1- When the carbocation formed from an alkyl halide, alkene, or alcohol can rearrange to one or more carbocations that are more stable, it usually does so, and the major products obtained from the reaction are usually those from the more stable carbocations.



Butylbenzene
(32–36% of mixture)

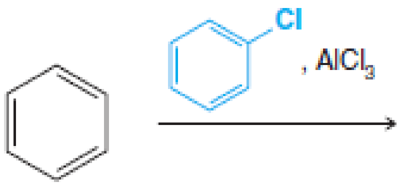
sec-Butylbenzene
(64–68% of mixture)

2- Friedel–Crafts reactions usually give poor yields when powerful electron-withdrawing groups are present on the aromatic ring or when the ring bears an NH2, NHR, or NR2 group. This applies to both alkylations and acylations.

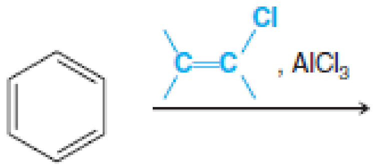


These usually give poor yields in Friedel-Crafts reactions.

3- Aryl and vinylic halides cannot be used as the halide component because they do not form carbocations readily

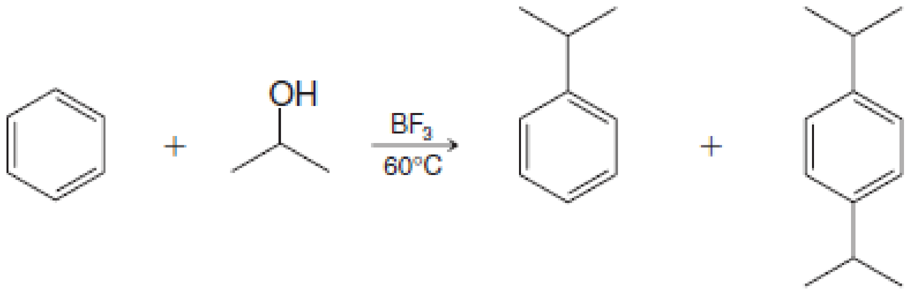


No Friedel-Crafts reaction because the halide is aryl



No Friedel-Crafts reaction because the halide is vinylic

4- Polyalkylations often occur.



Isopropylbenzene (24%)

***p*-Diisopropylbenzene (14%)**

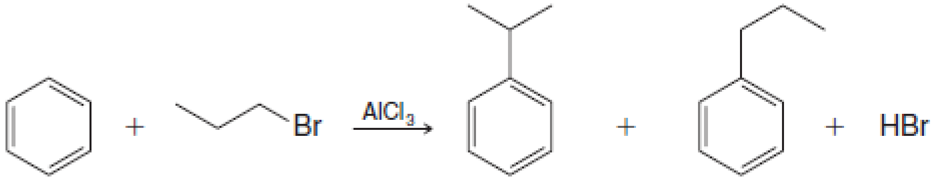
Polyacylations are not a problem in Friedel–Crafts acylations, however. The acyl group (RCO) by itself is an electron-withdrawing group, and when it forms a complex with AlCl3 in the last step of the reaction, it is made even more electron withdrawing.

This strongly inhibits further substitution and makes monoacylation easy.

Synthetic Applications of Friedel–Crafts Acylations:

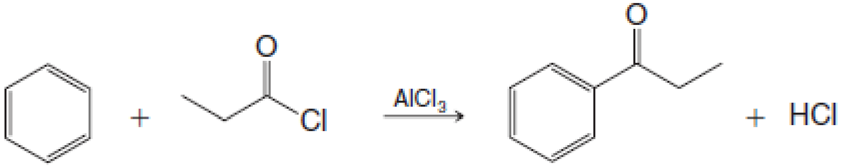
The Clemmensen Reduction

1- Rearrangements that happen in the Friedel–Crafts alkylations can be avoided by using Friedel–Crafts acylations



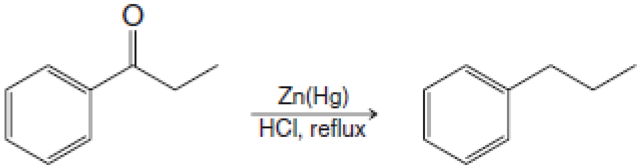
Isopropylbenzene (major product)

Propylbenzene (minor product)



Propanoyl chloride

Ethyl phenyl ketone (90%)



Ethyl phenyl ketone

Propylbenzene (80%)

2- When cyclic anhydrides are used as one component, the Friedel–Crafts acylation provides a means of adding a new ring to an aromatic compound.

One illustration is shown here. Note that only the ketone is reduced in the Clemmensen reduction step. The carboxylic acid is unaffected