

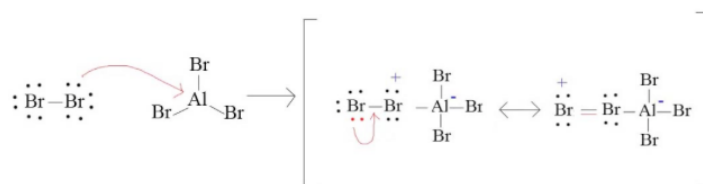
Year 2, Organic Chemistry, Chapter 07:

Electrophilic Aromatic Substitution (EAS) Reactions

(Benzene and its sister Aromatic compounds with delocalised π rings are called "Arenes")

Many of Benzene's substitution reactions require a Friedel-Crafts' catalyst

- The textbooks do not explain clearly **HOW** an FC catalyst works, and I believe that it is important to understand **how** things work, therefore even though I did talk about the formation of a Friedel-Crafts' (FC) catalyst moderately thoroughly in my introduction to Benzene in Chapters 5 and 6, I will now examine it in more detail – and please remember that *Benzene is a nucleophile* and that every Benzene molecule is protected by a huge area of electron density both above it and below it, **therefore it is only an electrophile that can react with Benzene** (in normal conditions).
- A number of the important electrophilic substitution reactions of Benzene require a Friedel-Crafts' catalyst for the reaction to take place (and without which the reaction would NOT take place at RTP), therefore let me show you how the University of California (Davis) portrays the dative-bonding of a Friedel-Crafts' catalyst that is acting as a Lewis Acid (i.e. one that is a lone pair acceptor) – and please note that in the diagram below, it is the $\text{Br}^{\delta+}$ species in the right hand bit of the diagram (shown as Br^+ where the "+" indicates its 'formal charge'¹) **which will be the electrophile that reacts with the Benzene molecule.**



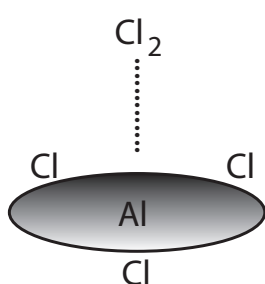
- UC (Davis) has used AlBr_3 here, but many chemists tend to specify FeBr_3 for Bromine and AlCl_3 for Chlorine reactions with Benzene. In truth, this is a sophistication that does not matter at all at 'A' Level.
- In everything that follows, please remember that the wording that I use is *anthropomorphic* (atoms cannot *give* or *donate*, **they do not have emotions**). **I am just using spoken words to try to explain a Mathematical reality – and inevitably, there will be a chasm between Language and Mathematics.** Please remember also that a yawning chasm opens up between depicting electrons as tiny little particles with minute mass, when in fact **most of the stuff that we talk about with regard to orbitals results from the analysis of the wave functions of electrons.**²
- The Br_2 molecule forms a dative bond with AlBr_3 by donating a pair of electrons to the vacant '3p' orbital in the Al atom in the AlBr_3 molecule. This therefore leaves the bonding Br atom short of an electron. Its companion Br atom (from the Br_2 molecule) therefore makes up for this by donating one of its lone pairs to the Br atom that is short of an electron (and UC Davis has shown this in red in the middle structure above). **You will now immediately see that since Al is not treating its four Br companions equally, AlBr_4 HAS to have the form of a Resonance structure.**

¹ A 'formal charge' is an electrostatic accounting system. It represents a relationship between bonded atoms. Wikipedia describes it thus: "In chemistry, a **formal charge** (FC) is the **charge** assigned to an atom in a molecule, assuming that electrons in all chemical bonds are shared equally between atoms, regardless of relative electronegativity".

² An electron is **simultaneously** both a particle AND a wave.

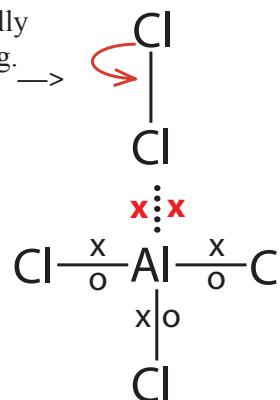
- When the outermost Br atom has donated a lone pair, it now becomes short of the electron that went into the vacant '3p' orbital in the Al atom – **and THAT is why the outermost Br atom in UC Davis' diagram has the "+" sign above it.**
- I trust that in all this you realised that the inner Br atom (the one with the "+" sign above it in the middle structure in UC Davis' diagram) could **NOT** act as the electrophile when AlBr_4 reacts with the Benzene molecule. It is only one of the **outermost** Br atoms that can act as the electrophile with regard to Benzene.
- When I first learnt about FC catalysts I just could not understand what was going on. None of it made sense to me. It was only when I analysed the different aspects of the Halogen carrying that I at last 'got it'. I find the UC Davis diagram easy because I understand what is going on, but if you do not understand what is going on, then perhaps my representation below might clarify the situation by a tiny amount. I have left out all the formal charges (*i.e.* all the "+" and "-" signs) from the diagram. I have not even used any of the " $\partial+$ " and " $\partial-$ " signs that we use to indicate electronegativity.
- I want you to see HOW the thing works. It is important because it is the basis of **ALL the Alkylation/Halogenation/and Acylation reactions of Benzene**. I have used AlCl_3 and Cl_2 in the diagram below.

I have drawn AlCl_3Cl_2 in only *one* of its Resonance forms



AlCl_3 is a trigonal **planar** species, and the Cl_2 approaches it either from above it or below it.

This bond will break heterolytically on collision with the Benzene ring. At that point the outer Cl species will become a Cl^+ species.

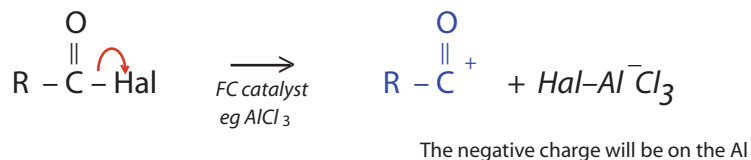


- AlCl_3 is a planar molecule and the Al atom is 'surrounded by'/'guarded by' three largish Cl atoms. The Cl_2 molecule is thus 'sterically hindered' if it tries to approach the AlCl_3 molecule in AlCl_3 's horizontal plane. For the Cl_2 molecule to bond with AlCl_3 therefore, Cl_2 must attack AlCl_3 from either below or above it. (*In my diagram, I have tried to show Cl_2 attacking AlCl_3 from above.*)
- Benzene is surrounded above and below by a cloud of electron density, therefore **it requires an electrophile (" E^+ ") to react with Benzene**. Therefore just as the AlCl_3Cl_2 species collides with the Benzene molecule, the outermost chlorine atom breaks away heterolytically from AlCl_3Cl_2 and becomes a Cl^+ species thus leaving the remainder of the species with a negative charge. **In all the text that follows the electrophile that attacks the Benzene molecule is designated as " E^+ ".**
- Now let us look at the whole substitution reaction.

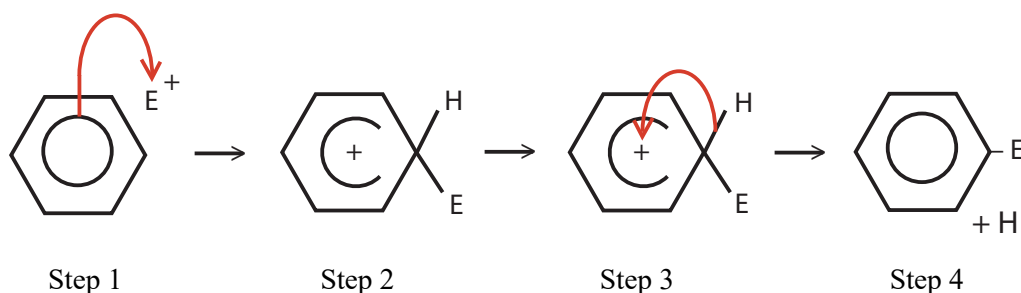
Halogenation, Alkylation and Acylation (all three of them require an FC catalyst)

- The three reactions above are extremely important in the synthesis of drug production where the manufacturers start with Benzene that has been obtained from the fractional distillation and then the Platforming/Reforming of crude oil extracted from under the ground or from under the sea (or from under the ice in Alaska and in Siberia).
- The reaction mechanism for the Halogenation, Alkylation, and Acylation of Benzene is the same for all three reactions, except that the identity of the attacking electrophile changes – therefore I am going to show the reaction mechanism using E^+ as the electrophile, and E^+ could be
 - Br^+ in the case of Bromination (this is a halogenation reaction)
 - Cl^+ in the case of Chlorination (this is a halogenation reaction)
 - $C_nH_{2n+1}^+$ in the case of Alkylation, and

d) in the case of Acylation it will be the “ $R-\overset{\overset{O}{\parallel}}{C^+}-$ ” depicted below (where the “ $-C=O$ ” is a Carbonyl group)³



- The common reaction mechanism for the Halogenation, Alkylation, Acylation and the Nitration of Benzene is thus



where " E^+ " is the attacking electrophile. My way of drawing what happens may be different from how some textbooks draw it, therefore let me explain in words what is happening.

- In the four steps involved

Step 1

The electrophile E^+ attached to the FC catalyst is attracted to the area of high electron density surrounding the Benzene ring, and Benzene then forms a dative bond with E^+ and Benzene thus “loses” one electron in doing so.

³ Just in case you need reminding, a Carboxylic Acid has the form “ $RCOOH$ ”, and if we tear off the “ $R-$ ” and the “ $-OH$ ” bits, we will be left with a “Carbonyl” (“ $-C=O$ ”) group. However, if you tear off **just** the “ $-OH$ ” bit from a Carboxylic Acid, then you will be left with the “Acyl” group (“ $RC=O$ ”) that we are now discussing.

Step 2

E^+ is now no longer short of an electron – but the Benzene ring has lost an electron and the ring has been broken⁴ and must therefore be shown as incomplete and with a positive sign in it. The C atom where substitution will occur is now temporarily bonded to both an H and the Electrophile.

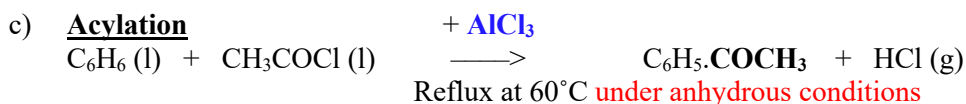
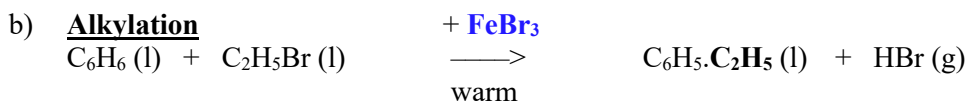
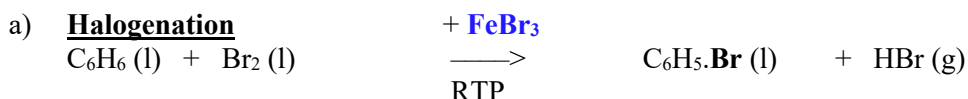
Step 3

The Hydrogen atom that is bonded to the C atom to which the electrophile is attached breaks away (as a proton) leaving behind its electron – and this now recreates the Benzene π ring!

Step 4

The reaction is now complete and the substitution reaction is finished. The proton that broke away will bond with the other “half” of the electrophile which at that stage is still attached to the FC catalyst.

- In the case of
 - a) **Halogenation** the molecule that reacts with the FC catalyst will be either Chlorine or Bromine (it is *much* more difficult to react Iodine with Benzene⁵), while in the case of
 - b) **Alkylation** it is sensible to use $C_nH_{2n+1}-Hal$ to bond with the FC catalyst (such as $AlCl_3/FeBr_3/etc$) to get the Alkyl Group “ $-C_nH_{2n+1}$ ” to bond with the Benzene, and in the case of
 - c) **Acylation** it is sensible to use $RCO-Hal$ for the $RC=O$ to bond with the FC catalyst.
- In this way, to accompany the E^+ species, there will always be a Halogen atom in the molecule to bond with the FC catalyst.⁶
- At ‘A’ Level you *are* required to know reaction equations as well as the reaction mechanisms, and I now give you three typical reaction equations below using an FC catalyst in each case (**shown in blue below**).



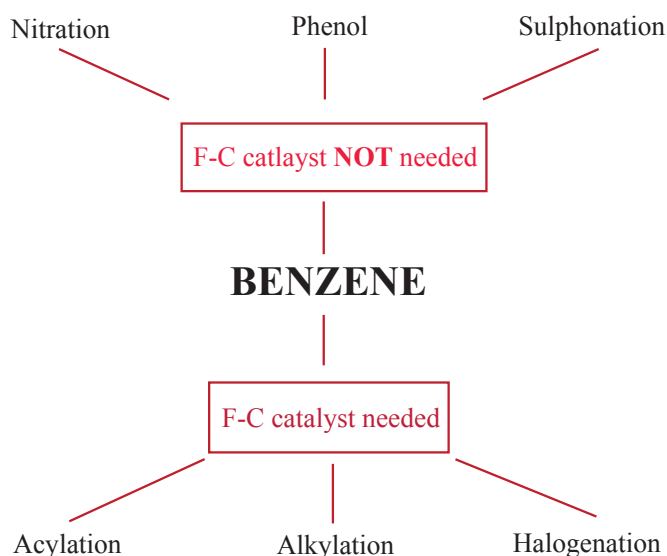
⁴ If the ring were not broken, then the C atom which now has the electrophile attached to it would have 5 bonds – and this it cannot have.

⁵ Iodobenzene can be obtained by reacting Benzenediazonium Chloride (BDAC) with Potassium Iodide. (“Azote” is the French name for Nitrogen, and that is where you get the term “diazonium” meaning two N atoms.)

⁶ I would therefore contend that the “halogen carrier” is actually carrying the *companion* species (but the term “companion” carrier would be ridiculously vague).

- In the exam, if you are asked about any of these three electrophilic substitution reactions of Benzene you will now be able to score 3 or 4 marks **within seconds** (and you **do** need to be able to answer questions *within seconds* or else you will not finish all the questions on the exam paper)!
- Halogenation will take place at RTP, but you would need to reflux the mixture at 60°C for **Acylation**, (whereas **Alkylation** with an FC catalyst should require nothing but warming).
- I have talked to you about about FC catalysts, and this little schema might be of help to you.

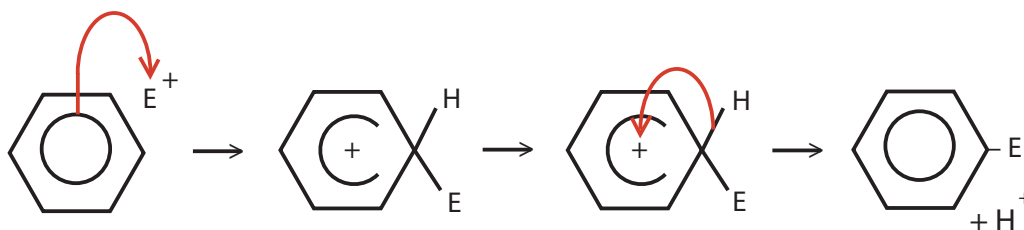
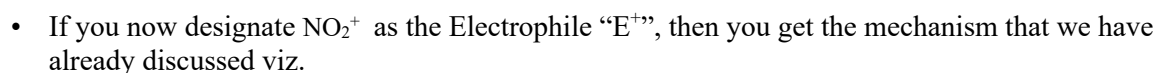
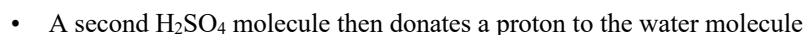
EAS Reactions of Benzene



Nitration (where the attacking electrophile is “ --NO_2^+ ”)

- I have on many occasions (both this year and last year) told you that Benzene is carcinogenic therefore you will NOT be allowed to (nor should you be allowed to) use it in English schools. In most cases you can use methyl benzoate at below 5°C (but my advice is just learn about it and watch it on youtube – it is much safer that way).
- Sulphuric acid acts as both the solvent and as the catalyst in this reaction, but **you must write “ $2\text{H}_2\text{SO}_4$ ” when you write your reaction equation in the exam.**
- As it happens, Nitration is another easy Benzene reaction where you can score the maximum marks available. All you need to remember is that you need an electrophile, and that the electrophile “ --NO_2^+ ” comes from Nitric Acid (HNO_3).⁷ $\text{HNO}_3 \longrightarrow \text{OH}^- + \text{NO}_2^+$.
- It is obtained by H_2SO_4 donating a proton to HNO_3 , and then H_2O^+ breaks away from the NO_2 by heterolytic bond fission thus creating H_2O and NO_2^+ .

⁷ $\text{HNO}_3 \longrightarrow \text{NO}_2^+ + \text{OH}^-$.



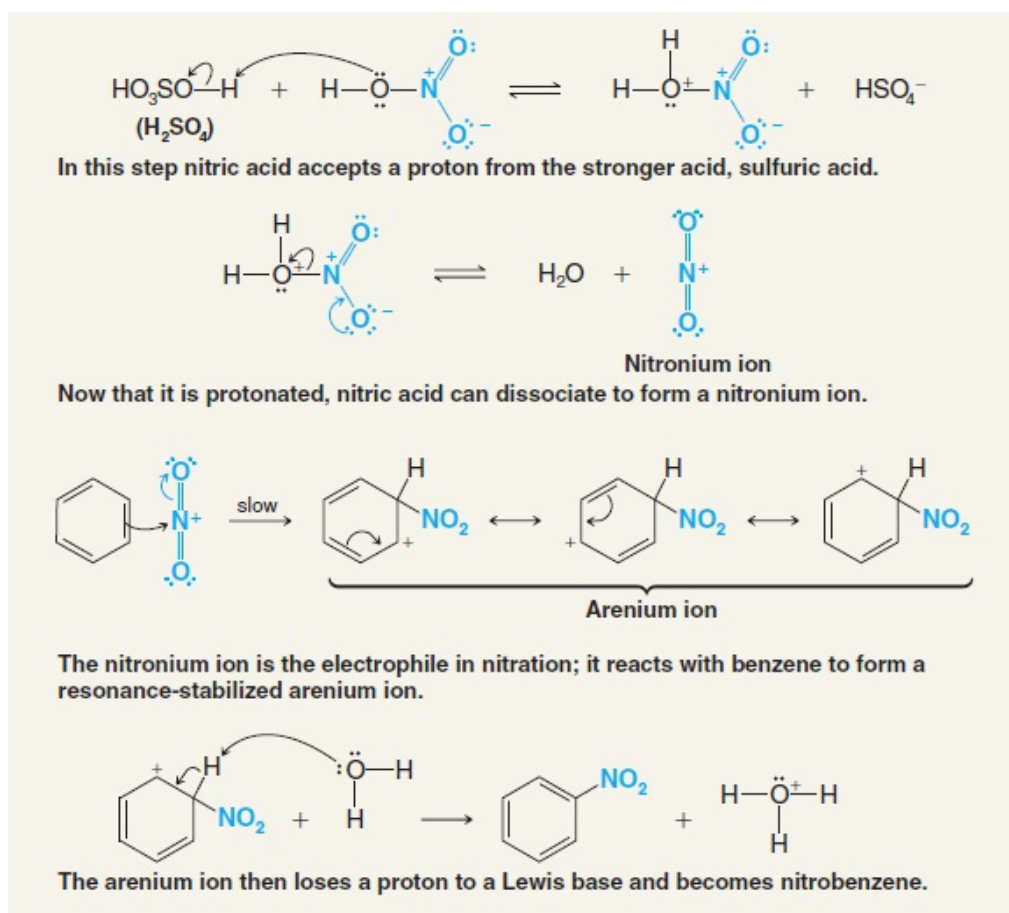
- $$\text{C}_6\text{H}_5\text{NO}_2 + \text{H}^+ + \text{H}_3\text{O}^+ + 2\text{HSO}_4^- \longrightarrow \text{C}_6\text{H}_5\text{NO}_2(\text{aq}) + \text{H}_2\text{O} + 2\text{H}_2\text{SO}_4.$$

- $$\text{HNO}_3 (\text{aq}) + \text{C}_6\text{H}_6 (\text{l}) \xrightarrow{\text{Reflux at } <60^\circ\text{C with conc. H}_2\text{SO}_4} \text{H}_2\text{O} (\text{l}) + \text{C}_6\text{H}_5\text{NO}_2 (\text{aq})$$

- If the reactants are refluxed at 95°C then 1,3-**D**initrobenzene will be obtained. For a reason that I will tell you about in Chapter 8 (*the process can involve either Activation or Deactivation*) the Nitro group **deactivates** the Benzene ring), making Nitrobenzene less reactive than Benzene. To obtain the high explosive **Tri**Nitro**T**oluene (TNT) an *activating* group such as “-CH₃” must first be attached to a Benzene ring (to give a compound called Toluene, C₆H₅.CH₃) and then Toluene must be Nitrated to give CH₃.C₆H₂-2,4,6-(NO₂)₃.

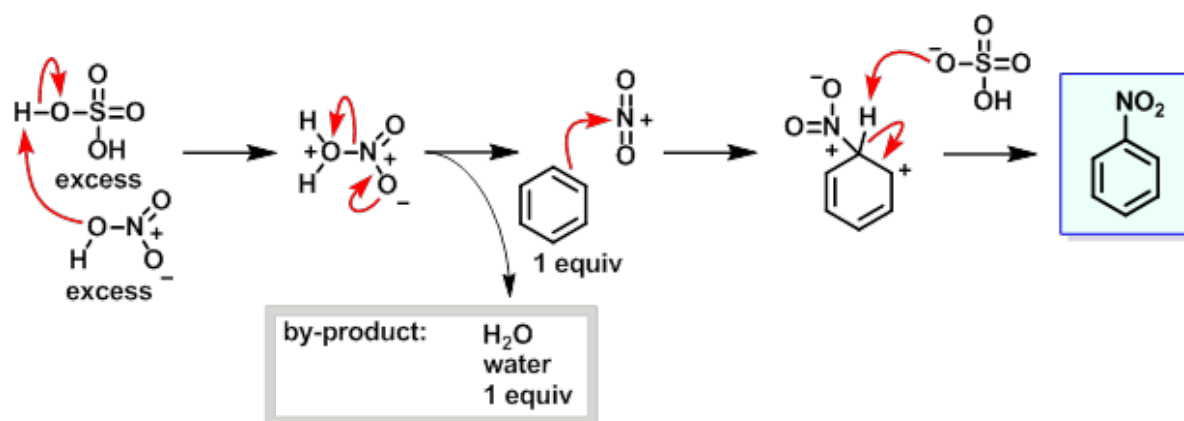
- The following is a nice little explanation of what is happening, and I found it on

[https://chemistry.stackexchange.com/questions/14883/why-does-a-brønsted-lowry-acid-accept-proton-from-stronger-acid](https://chemistry.stackexchange.com/questions/14883/why-does-a-br%C3%B8nsted-lowry-acid-accept-proton-from-stronger-acid)



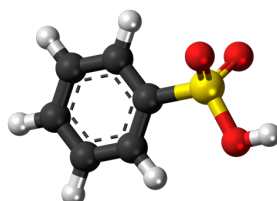
- This is what the accompanying text said “*The first step of the mechanism would not, on its own, happen to a large extent – protonating nitric acid is unfavorable, so the equilibrium would lie far to the left. However, the second step of the mechanism is highly favorable (entropically)⁸, so it quickly consumes what little H_2NO_3^+ is produced by the first step. This drives the overall reaction forward by Le Chatelier's principle.*”
- I imagine that the author was an American gentleman because the spelling is not English but US. I have put in here because very soon we will need to start talking about Inorganic A2 Chemistry and about things such as “slow steps” and fast steps”.
- Here is another pictorial representation of the same reaction (from Common Organic Chemistry.com)

⁸ We will talk about “entropy” later on this year.



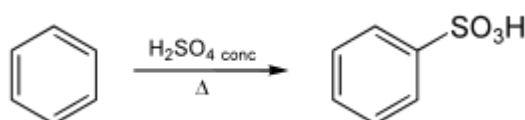
NB I am putting these diagrams here in order to make you familiar with reaction mechanisms/remind you of the use of curly arrows/etc.

Sulphonation to give Benzenesulphonic Acid, $\text{C}_6\text{H}_5\text{SO}_3\text{H}$ (also called Phenylsulphonic acid)



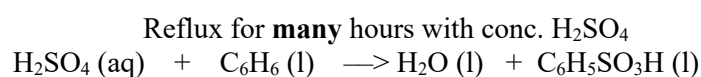
Source: Wikipedia

- Interestingly, Wikipedia says “*Benzenesulfonic acid is prepared from the sulfonation of benzene using concentrated sulfuric acid:*”



This conversion illustrates aromatic sulfonation, which has been called "one of the most important reactions in industrial organic chemistry".

- That is Wikipedia’s statement and not mine, and sadly, I know next to nothing about Industrial Chemistry therefore I cannot comment on the claim, but Benzenesulphonic Acid is certainly extremely important in the manufacture of drugs/dyes/and detergents therefore I am happy to accept Wikipedia’s claim.
- The reaction equation for Sulphonation is



but the reaction can be speeded up very considerably by refluxing Benzene with so-called “*fuming*” sulphuric acid (*which is SO_3 (g) dissolved in sulphuric acid*).

- Let me remind you of the electrophilic substitution reactions of Benzene that we have talked about so far (and this next table comes from the University of California, Davis).

Reaction Type	Typical Equation			Electrophile E ⁽⁺⁾
Halogenation:	C ₆ H ₆ + Cl ₂ & heat FeCl ₃ catalyst	—→	C ₆ H ₅ Cl + HCl Chlorobenzene	Cl(+) or Br(+)
Nitration:	C ₆ H ₆ + HNO ₃ & heat H ₂ SO ₄ catalyst	—→	C ₆ H ₅ NO ₂ + H ₂ O Nitrobenzene	NO ₂ (+)
Sulfonation:	C ₆ H ₆ + H ₂ SO ₄ + SO ₃ & heat	—→	C ₆ H ₅ SO ₃ H + H ₂ O Benzenesulfonic acid	SO ₃ H(+)
Alkylation: Friedel-Crafts	C ₆ H ₆ + R-Cl & heat AlCl ₃ catalyst	—→	C ₆ H ₅ -R + HCl An Arene	R(+)
Acylation: Friedel-Crafts	C ₆ H ₆ + RCOCl & heat AlCl ₃ catalyst	—→	C ₆ H ₅ COR + HCl An Aryl Ketone	RCO(+)

- Let me also remind you of the little information tree for Benzene that I constructed, and I would strongly urge you to construct info trees for every topic in every science subject that you are doing. On something like 20 pieces of paper (for each subject) you will be able to summarise **everything** that you need to know, and if you go through these info trees the last thing at night and on the way to and from school, then you will get **very** high marks in your 'A' Level exams. (This practice will also be very useful to you at University.)

Both Alkylation and Acylation must be carried out under anhydrous conditions.

The SUBSTITUTION reactions of Benzene

