

Year 2, Organic Chemistry, Chapter 08:

Activation and Deactivation

in preparation for the Substitution Reactions of Benzene

(You may find the textbook descriptions rather difficult. My description may be rather easier to understand.)

Activation and Deactivation of the Benzene Ring

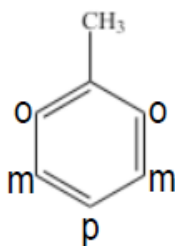
- I think that the usage of the terms relating to Activation and Deactivation is rather sloppy (*and I am not sure why we Chemists tend to be so sloppy compared to Mathematicians and Physicists*). I shall therefore try to be more precise in my usage of the terms, and for “Activation” I shall use the phrase “**2/4/6 Activation**”, and for “Deactivation” I shall use the term “**2/4/6 Deactivation, but 3/5 Activation**” of the Benzene ring – and you will see exactly what I am talking about in next few sentences.

2/4/6 Activation of the Benzene ring

- A Benzene ring is created by the delocalisation of the π electrons in the overlapping unhybridised ‘p’ orbitals of the six C atoms in Benzene, and **any substituent that increases the electron density in that π cloud** (i.e. the “+M” effect, or so-called *Electron Donating Effect*¹) will **activate** the Benzene ring, while anything that decreases the electron density of the π cloud (the “-M” effect, or so-called *Electron Withdrawing Effect*) will **deactivate** it (and please remember that the “I effect” is always superseded by the “M effect”). If you need to re-read Chapter 3, then please do so now.
- In Chapter 6 I talked quite extensively about OMP, so let us start this conversation with that.

The Ancient Greek words “ortho”, “meta”, and “para” (OMP, or “Oh My Pappa”)

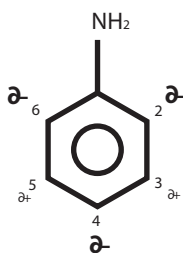
- Using the **modern numbering system**, “ortho” is position number “2 or 6” on the π ring (*and please remember that the difference between position No.2 and position No.6 results merely from the position where you stand in relation to the Benzene ring, with position No 2 being equivalent to position No 6*), “para” is position number “4”, while “meta” is position number “3 or 5”.



Here you can see clearly that position No.2 and position No.6 are equivalent to each other, and that position No.3 and position No.5 are equivalent to each other. One situation looks at the molecule from the front and the other looks at it from the back.

¹ The substitution of an H atom on a Benzene ring by a species or group that increases the electron density on the delocalised π ring. The electron density is increased but, despite the name “electron donating” no electrons are actually donated – and in “electron withdrawing” no electrons are withdrawn. It is only electron density that is increased or reduced.

- There are complicated reasons that can be given to explain why activation causes electrophiles to substitute/replace H atoms at positions **2,4 and 6** whereas deactivation causes electrophiles to substitute/ replace at positions **3 and 5** – but you might find my following *non-complicated* explanation moderately helpful.
- If something pushes electron density onto the π ring at position 1 (and if you increase electron density, then that entity will become more electronegative), then the density will flow down both sides of the π ring and meet at position 4, and **position 4 will now have a “ δ^- ” charge**. Positions 3 and 5 will then have a “ δ^+ ” charge and positions 2 and 6 will have a “ δ^- ” charge. Chemists say that positions 2,4 and 6 have been **activated** (and what they mean is that those positions have become *slightly* more electronegative **and thus become more ready to accept an electrophile**), and attacking electrophiles will join on at these positions and replace the H atoms that are already there.

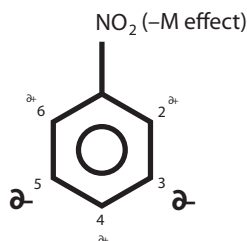


- As you can see, by pushing electron density onto the π ring, we have **increased** electron density at positions 2/4/and 6 and *decreased* electron density at positions 3 and 5. An electrophile will therefore be attracted to positions 2/4/6 of the Benzene ring and will replace the H atom that is there.

2/4/6 Deactivation of the Benzene ring (but Activation at 3/5)

(Some textbooks call this “electron withdrawing”, although in fact it is only electron **DENSITY** that is altered.)

- In contrast, any species that withdraws electron density² from the π ring (e.g. “ NO_2^+ ”), will pull the electron density along both sides of the ring and leave positions 2,4 and 6 as “ δ^+ ” positions, therefore electrophiles will attach at the 3 and 5 positions because these are now the “ δ^- ” positions!



NB Deactivation does not actually “deactivate” the Benzene ring. **It just deactivates positions 2/4/and 6, and instead it activates positions 3 and 5.**

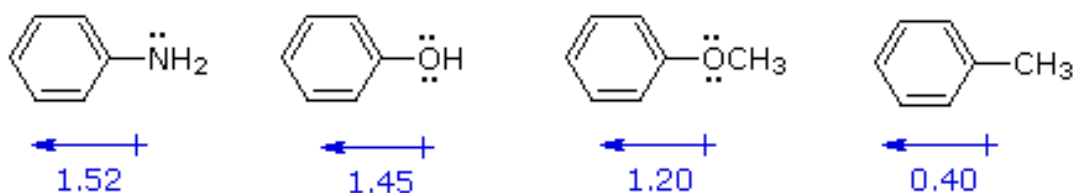
It really is very simple when you get it!

² Elements to the right of the Periodic Table are more electronegative than the elements that lie to the left of them, therefore we are talking mainly about a Halogen or a **highly electronegative element such as Oxygen or Nitrogen that is attached to an atom that is attached to a C atom in the Benzene ring**. In “ NO_2^+ ”, the O atoms are more electronegative than the N atom therefore they pull electron density off the N atom, and the N atom in turn pulls electron density off the C atom and thus off the delocalised π ring.

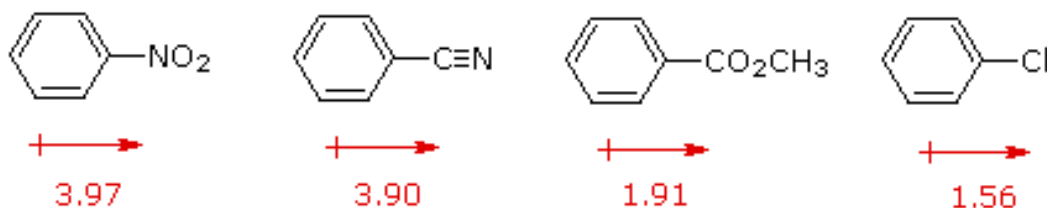
The following are 2/4/6 Activating Species

- **Alkyl Groups** (i.e. $-\text{C}_n\text{H}_{2n+1}$) because they “push” electron density along the σ bond (“+I effect”)
- **A Halogen species** (i.e. $-\text{Hal}$) (where an “-I” effect is over-ridden by a “+M effect”)
- **Any species that contains one or more lone pairs in a ‘p’ orbital that lies in the same vertical plane as the ‘p’ orbitals in the Benzene π ring** (e.g. $-\text{O}-$, $-\text{OH}$, $-\text{NH}_2$, $-\text{O}-\text{C}_n\text{H}_{2n+1}$, $-\text{OR}$, $-\text{NHR}$, $-\text{NRR}$, etc.³) because their lone pairs get locked into the Benzene π ring and increase its electron density (again this is a +M effect).
- This is how Prof William Reusch of Michigan State University shows some of the activating and deactivating substituents on a Benzene ring. [Look at the direction of the arrows!](#) (Do not worry about the size of the electronegativity numbers. You do not need them for UK ‘A’ Level Chemistry.)

Activating Substituents



Deactivating Substituents



2/4/6 De-activating Species (but they ACTIVATE at 3/5)

- **A Carbonyl ($-\text{C}=\text{O}$) Group** in a Carboxylic Acid/an Aldehyde/a Ketone/and an Ester) where the C atom in the Carbonyl Group is attached to a C atom in the Benzene ring. The Oxygen atom in the Carbonyl Group is the second most electronegative atom in the Periodic Table and (because it is locked in through a C atom to one of the C atoms in the Benzene ring) it so-to-speak just hovers up electron density off the Benzene π ring. This is a -M effect.
- **An N atom** (attached to a C atom on the Benzene ring) **when it has one or more O atoms attached to it** (e.g. $-\text{NO}_2$) for the same reason as above, but please note that when the N atom has a less electronegative atom attached to it (e.g. as in $-\text{NH}_2$) then the electrons in the unhybridised ‘p’ orbitals of the N atom get locked into the Benzene π ring and *increase* the electron density of the π ring at 2/4/6 (rather than 3/5).
- **A $-\text{C}\equiv\text{N}$ species** where the C atom is bonded to a C atom in the Benzene ring (for the same reason as the previous two groups).

³ where “R” is an alkyl group.

- **An S atom bonded to one or more O atoms** (e.g. $\text{-SO}_3\text{H}$) where the S atom is bonded to a C atom on the Benzene ring (again for the same reason).
- **An Alkyl Group with one or more Halogen species attached to it** (because the Halogens will pull electron density off the C atom and electron density will then in turn be pulled off the π ring).
- The table below is from UC Davis (but you will have to remember that “ortho-para” means “Activates at 2/4/6”, and “meta” means “Activates at 3/5”.

Table of Substituents

Ortho-Para Directing				Meta Directing	
Strong Activating	Moderately Activating	Weakly Activating	Weakly Deactivating	Moderately Deactivating	Strongly Deactivating
-NH ₂ -NHR -OH -OCH ₃	-NHCOR -OCOR	-CH ₃ -phenyl	-F -Cl -Br -I	-COH -COCH ₃ -COOCH ₃ -SO ₃ H	-NO ₂ -CF ₃ -CCl ₃

and the table on the next page (from Dr Ian Hunt of the University of Calgary) is even more detailed where “EDG” means electron donating group (+M effect), and “EWG” means electron withdrawing group (–M effect) – *but the table might be too detailed for you*. I have included it merely so that you can have a look at all the different species that you could encounter.

- In the exams, there has been a tendency of late (post Mr Gove’s changes in 2015, to throw things at you that are NOT in the Syllabus to see whether or not you will be able to apply the principles that you have learnt (even if it is to something that you have **not** learnt about).

NB “Activating” means that the overall electron density on the π ring has been **increased** and that positions 2/4/and 6 are now δ^- , and “deactivating” means that the overall electron density on the π ring has been **decreased** and particularly so at positions 2/4/6 but that **positions 3/5 are now δ^-** .

Activating EDG	$\text{—}\ddot{\text{O}}\text{—}$ $\text{—}\ddot{\text{N}}\text{R}_2\text{—}$ $\text{—}\text{NH}_2\text{—}$ $\text{—}\ddot{\text{O}}\text{H—}$ $\text{—}\ddot{\text{O}}\text{R—}$ $\text{—}\text{NHCO—}$ $\text{—}\text{CO—}$ $\text{—}\text{R—}$ $\text{—}\text{C}_6\text{H}_5\text{—}$ $\text{—}\text{CH=CR}_2\text{—}$	Strongly Activating	ortho / para directing
		Moderately Activating	
		Weakly Activating	
Reference	$\text{—}\text{H—}$		
Deactivating EWG	$\text{—}\text{X—}$ $\text{—}\text{CHO—}$ $\text{—}\text{CR—}$ $\text{—}\text{COR—}$ $\text{—}\text{COOH—}$ $\text{—}\text{CCl—}$ $\text{—}\text{CF}_3\text{—}$ $\text{—}\text{C}\equiv\text{N—}$ $\text{—}\text{SO}_3\text{H—}$ $\text{—}\text{NH}_3^+\text{—}$ $\text{—}\text{NR}_3^+\text{—}$ $\text{—}\text{NO}_2^+\text{—}$	Weakly Deactivating	meta directing
		Moderately Deactivating	
		Strongly Deactivating	
Most Deactivating			

These effects are a combination of **RESONANCE** and **INDUCTIVE** effects (see [next page](#))

The effects are also important in other reactions and properties (e.g. acidity of the substituted benzoic acids).

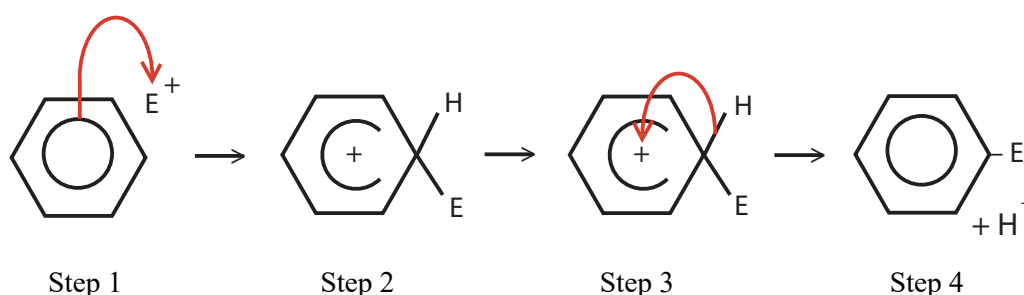
Here are some **general pointers** for recognising the substituent effects:

- The H atom is the standard and is regarded as having no effect.
- **Activating** groups increase the rate
- **Deactivating** groups decrease the rate
- **EDG = electron donating group**
- **EDG** can be recognised by lone pairs on the atom adjacent to the π system, eg: —OCH_3
- **except** —R , —Ar or —vinyl (hyperconjugation, π electrons)
- **EWG = electron withdrawing group**
- **EWG** can be recognised *either* by the atom adjacent to the π system having several bonds to more electronegative atoms, *or*, having a formal +ve or δ +ve charge, eg: $\text{—CO}_2\text{R}$, —NO_2
- **EDG / activating** groups direct *ortho / para*
- **EWG / deactivating** groups direct *meta*
- **except** halogens (—X) which are deactivating **BUT** direct *ortho / para*
- **EDG** add electron density to the π system making it **more nucleophilic**
- **EWG** remove electron density from the π system making it **less nucleophilic**.

- My last word on this subject is that we talk glibly about Activation and Deactivation and there is the danger of forgetting that every Benzene molecule is surrounded by/protected by a huge area of electron density both above it and below it – and this makes, in a sense, every bit of the molecule attractive to an electrophile. OK, some bits may be more attractive than others (2/4/6 in some circumstances and 3/5 in other circumstances), but the truth is that this is all relative.
- We are therefore talking about **relative** attraction, and electrophiles will substitute mainly at 2/4/6 or mainly at 3/5 – but not exclusively so. The table below (from Michigan State University) shows this very clearly). Depending on the E^+ attacking species, a tiny amount (but at most 10%) of substitution actually does occur in the non-favoured positions.

Y in C ₆ H ₅ -Y	Reaction	% Ortho-Product	% Meta-Product	% Para-Product
-O-CH ₃	Nitration	30-40	0-2	60-70
-O-CH ₃	F-C Acylation	5-10	0-5	90-95
-NO ₂	Nitration	5-8	90-95	0-5
-CH ₃	Nitration	55-65	1-5	35-45
-CH ₃	Sulfonation	30-35	5-10	60-65
-CH ₃	F-C Acylation	10-15	2-8	85-90
-Br	Nitration	35-45	0-4	55-65
-Br	Chlorination	40-45	5-10	50-60

- 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.

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.

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.

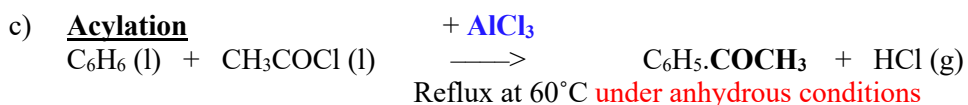
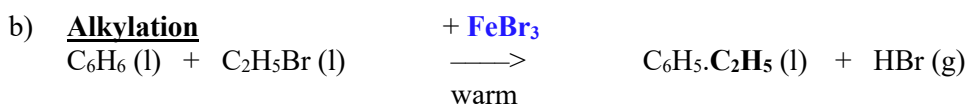
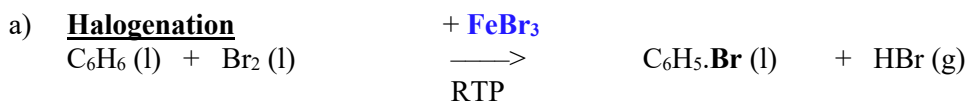
Step 3

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**).



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).
- In Chapter 5 we talked about FC catalysts, and this little schema might be of help to you.

EAS Reactions of Benzene

