Electrophilic Aromatic Substitution (EAS) is a substitution reaction usually involving the benzene ring; more specifically it is “a reaction in which the hydrogen atom of an aromatic ring is replaced as a consequence of electrophilic attack on the aromatic ring.” (Thinkbook)

**Benzene**
Benzene is best represented as a resonance hybrid: \( \text{[resonance hybrid]} \)

It has 120° bond angles and sp² carbons. It is a planar molecule with parallel and overlapping p-orbitals. Benzene experiences a high degree of resonance and aromaticity which means any reaction breaking a double bond will have very high activation energy. Finally, benzene has electrons above and below the ring making it nucleophilic and subject to electrophilic attack.

**EAS reactions all follow the same general two-step mechanism.**

**Step 1:** An electrophile attacks the pi electrons of the aromatic benzene ring which results in the formation of a resonance stabilized carbocation. This carbocation is called the arenium ion and has three resonance contributors. Electrophilic attack is a very slow process. It is endergonic and has high activation energy due to the loss of aromaticity.

**E=electrophile**

**notice the arenium ion:**

**Step 2:** The carbocation intermediate is attacked by a base and loses a proton. These electrons are used to reform a pi bond and restore aromaticity. As opposed to the first step, this step is fast and exergonic because aromaticity is regained. It is important to note that the carbocation loses a proton where the electrophile attacked the benzene ring.

**B=base**
Looking at the reaction profile of EAS, you will see the energy required for step 1 to proceed is very large. Like $S_{N_1}$ and E1 reactions, the rate-determining step (RDS) is the formation of the carbocation.

Looking back at the three carbocation fates (capture a nucleophile, lose a proton and form a pi bond, or rearrange), you might be wondering why the carbocation loses a proton and does not capture a nucleophile. Capturing a nucleophile would result in an addition reaction which gets rid of the positive formal charge but does not restore aromaticity.

The Five Most Common EAS Reactions
Every EAS reaction follows the same mechanism and differs only in how the electrophile is formed.

1. **Halogenation**

Functional groups: halides (Br, Cl)

Mechanism:

- Under certain environmental conditions, halogenation can occur by two other mechanisms:

  - Bromine cation attacks benzene.
  - Ionization of FeBr$_4^-$
• You also might ask why is FeBr₃ necessary for the reaction to occur and not just Br₂?
  o Disrupting aromaticity is hard to do and requires a strong electrophile- Br₂ alone has no open octet, no + and no formal positive charge. When it approaches benzene, the electron clouds repel each other creating a brief polarization/ induced dipole due to Van der Waals interactions but this still is not a strong enough electrophile. Using a Lewis acid such as FeBr₃ or AlBr₃ increases the polarity of the Fe-Br bond and makes Br a better electrophile.
• Halogenation also occurs with Cl₂, FeCl₃ and AlCl₃.

Problem: Draw the mechanism of the following reaction including all resonance contributors and the polarization of Cl₂.

Solution:

2. Sulfonation with SO₃ or SO₃H⁺ (sulfonic acid)
• This is the only reversible EAS reaction.
3. Nitration
Functional group: nitro (\(^{\circ} \text{NO}_2\))

Formation of nitronium cation:

In order for OH to leave, it must be protonated by an acid.

**Notice the similarity between the formation of the electrophile in sulfonation and nitration.

Mechanism:

For Practice: Try drawing the three resonance contributors of the carbocation.

4. Friedel-Crafts alkylation (alkyl group, R)

**Note: any process can be used to make the carbocation.

5. Friedel-Crafts acylation (\(^{\circ} \text{O} \ C–R\), acylium ion)

Mechanism:
The Effects of Substitution on EAS

- General reaction can produce three products

\[ \text{E} \rightarrow \text{X} + \text{Y} + \text{Z} \]

\( E = \text{electrophile} \)

- The preferred product depends on one of three factors: sterics, probability, or the mechanism itself which are determined by the properties of the substituent.
  - The stability of the carbocation is what matters the most. In general, the factors are ranked:
    - Mechanism > probability > sterics (only when sterics aren’t severe)

- Electron donating groups (EDG)
  - Ex. Alkyl groups, aryl, vinyl, alkynyl, hydroxyl, ether and amine
  - These groups donate electron density by inductive electron donation and through donation by resonance
  - Substituents that donate electron density stabilize the carbocation which increases the rate of EAS
  - Electron donating groups are also called activators which increase the EAS reaction rate by making the benzene ring more reactive
  - EDG are ortho/para directors meaning electrophilic attack will result in the new atom forming a bond in the ortho or para position
  - Ex.

- Electron withdrawing groups (EWG)
  - Ex. Nitro carbonyl, trifluormethyl, ammonium, any groups with a positive charge
  - These substituents remove electron density from the aromatic ring, reducing benzene’s nucleophilicity and slowing the rate of electrophilic attack
  - Electron withdrawing groups are deactivators and meta directors.
  - Ex.

- Halogens are a special case. They provide a small resonance contribution making them ortho/para directors but, due to a significant inductive effect, halogens are also deactivators.

- What happens when there are two substituents?
  - If the substituents direct to the same position, then the electrophile will attach there.
  - If the substituents are different, the activating substituent “will win out.” (Bruice)
  - If the substituents are similar, “a mixture of products will result.” (Bruice)
Why does EAS matter?

- Synthesis of Allura Red AC, an Azo Dye
  - Azo dyes are reds, yellows and oranges. They are highly soluble in water and were discovered to be carcinogens.
  - Synthesized in a process using diazo coupling. This reaction is very sensitive to sterics and results in the formation of $\text{N=}=\text{N}$.
  - Due to sterics, there is often a cis and trans product with the trans being more stable.

![Chemical reaction and structure diagram]

Ortho attack here is favored due to greater stability despite some sterics.

Result: highly conjugated molecule

**Images and information taken from Chemistry 14D Thinkbook Winter 2006 and Organic Chemistry by Paula Bruice 4th edition.**