Organic Reactions 2
Elimination

There are four similar reactions that organic compounds can undergo: S_N1, S_N2, E1 and E2. This worksheet will cover the elimination reactions, and the competition between elimination and substitution reactions (covered in *Organic Reactions 1*).

In both cases of elimination, an organic molecule loses one hydrogen atom and one leaving group, bonded to two adjacent carbons in the substrate. The leaving group is bonded to the **α-carbon** (alpha-) and the hydrogen is bonded to the **β-carbon** (beta-). During an elimination reaction, electrons move in a sort of chain reaction from the β-carbon to the α-carbon to form a double bond, producing an alkene. Elimination reactions are more likely to occur at higher temperatures.

While there's usually only one choice for a halogen and α-carbon in most reactants, there may be a number of choices for the β-carbon — organic compounds generally have many sources of hydrogen. Thus, there are usually multiple products in elimination reactions. **Zaitsev's rule** will often help us identify the major product: the more substituted alkene is the favoured product. By "substituted" here, we mean having the most of the hydrogens on the α- and β-carbons replaced with some other structure.

NUCLEOPHILES AND BASES

We looked at nucleophiles in substitution reactions; many of those species are also bases, and they will act as a base in elimination reactions, taking a hydrogen atom from the substrate. (Don't be confused by the term "strong base"! Remember, a strong acid is one that will give up all its acidic hydrogen; a strong base will do the opposite, taking on a hydrogen very easily. Since we're looking at bases here as taking H^+ —accepting a proton — we're specifically talking about **Brønsted-Lowry bases**, or **BLBs**.)

So what *is* the difference between nucleophiles and bases? The exact definition of a nucleophile is a species that specifically donates an electron pair to an atom *other than hydrogen*, generally carbon. It's a **Lewis base** that's not acting on hydrogen. (In general, every BLB is also an example of a Lewis base, but the exclusion of hydrogen in the definition of "nucleophile" separates the two terms further.)

E2 REACTIONS: COLLISIONS, again

There are strong parallels between the mechanisms of the elimination reactions and the substitution reactions. Like the S_N2 reaction, the E2 reaction is a collision between the substrate and another molecule, and the whole reaction occurs in a single step.
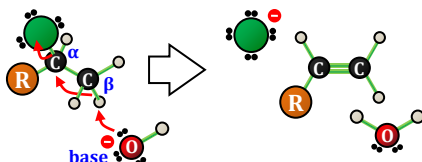
Conditions must be favorable. For the E2, there's only one question to worry about:

● *How strong is the base?* The base needs to be relatively strong in order to take a hydrogen atom from the substrate. Generally it must be stronger than the leaving group

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is (which is typically a halogen atom). The hydroxide ion (OH^-) and alkoxide ions (RO^-) are good for this purpose. (To simplify things, your instructor may have mentioned ethoxide, $CH_3CH_2O^-$, as a good example of a strong base.)

A BLB collides with a hydrogen atom on a possible β-carbon. If the base is strong enough, it takes the H^+ from the atom but leaves the electrons in the bond behind. A chain reaction of moving electrons ejects the leaving group and creates a double bond. It's probably easier to see what happens with a diagram: the tail of each arrow starts at an electron pair (lone pair or bond), and points to where those electrons go.

Notice that no mention has been made as to whether the carbons in question are primary, secondary or tertiary. For the E2 reaction, all of these situations are possible as long as there's an available hydrogen on the β-carbon.
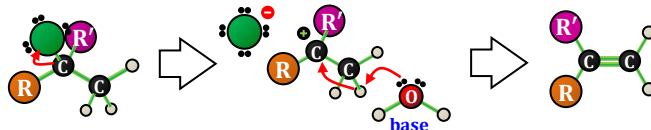
E1 REACTIONS: DISSOCIATIONS, again

Like the S_N1 reaction, the E1 reaction is a two-step process in which the initial step is the spontaneous dissociation of the leaving group, forming a carbocation. The next step neutralizes the carbocation by giving the affected carbon some negative charge.
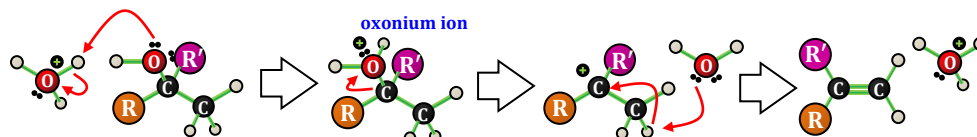
In the S_N1 reaction, that negative charge comes from the nucleophile; in an E1, it's an electron pair from the β-carbon after it releases a hydrogen atom, very similar to the process in E2. The questions to ask are:

● *How good is the leaving group?* Unlike the S_N1 reaction, the E1 reaction can occur with either a good leaving group or a poor leaving group. As in the substitution reaction if the leaving group is good, e.g. a halogen, the initial step is much more likely to occur. If the leaving group is poor, then the reaction must occur in acid so that the leaving group can be improved, as we'll discuss in a moment.

● *How stable is the carbocation?* As with the substitution reaction, the substrate must have a tertiary (or maybe secondary) carbon to support a carbocation.

● *How strong is the base?* The presence of a strong base will probably cause the E2 reaction to occur instead of E1. A weaker base favours E1 because even a weak base will relieve the strain caused by the carbocation.

With a halogen as the leaving group, the mechanism is straightforward. The incoming base removes a hydrogen atom from the β-carbon, and the electron pair that formed the bond moves toward the α-carbon to neutralize the carbocation.

If the potential leaving group isn't strong, such as a hydroxy group (−OH) then it will not spontaneously dissociate, but it may be converted into one that will. In an acidic environment (such as with H_2SO_4 or H_3PO_4), the OH can pick up an extra hydrogen to form an **oxonium ion**, an ion in which an oxygen atom has a positive charge. The oxonium ion is even less stable than a carbocation, so it will react quickly. The ion now has an H_2O group which is a much better leaving group — the molecule undergoes dehydration (i.e., it releases water), and the positive charge transfers to the adjacent carbon atom, forming a carbocation. From there the process is the same as for any elimination reaction.

COMPETITION BETWEEN THE REACTIONS

The hard part of this material is knowing which reaction is going to occur, and under what conditions. Your instructor may have boiled this all down to:

Ethoxide is the only strong base we'll get; if appears with an alkyl halide it's an elimination, and otherwise it's a substitution. Alcohols with H_2SO_4 or H_3PO_4 undergo elimination as well.

This is very simplified! The reality is more complicated. The biggest factor that determines which reaction will occur is the structure of the substrate. We can classify the reaction types based on structure.

Tertiary Alcohols
The only mechanism we've covered is an E1 reaction, as indicated above.

Tertiary Alkyl Halides
Among tertiary halides, the S_N2 reaction cannot happen at all; the only kind of substitution that can occur is S_N1. Both the E1 and E2 reactions can occur. The initial rate-determining step of the S_N1 and E1 reactions for any substrate, not just this type, are the same, so when one is possible, there will always be competition between them, and it's hard to know what's favoured. The E2 reaction is favoured in the presence of strong bases; the unimolecular reactions are favoured otherwise.

Primary Alkyl Halides
This is the simplest case: Among primary halides, the S_N1 and E1 reactions cannot happen at all. The E2 reaction is favoured in the presence of strong bases; otherwise the S_N2 reaction is favoured.

Secondary Alkyl Halides
With secondary halides all four kinds of reaction are possible, and the actual outcome is based on a number of factors, so prediction is quite hard. (As such, when trying to synthesize a particular compound, this starting point isn't usually used.) Without a strong base the E2 reaction doesn't occur at all, and the S_N2 reaction is more likely.

These are general guidelines and other factors (choice of solvent, temperature, steric hindrance of reactants, …) may change the likelihood of each kind of reaction.

EXERCISES

A. Give the major product in the following E2 reactions with heat, if an E2 reaction is possible. By the standard IUPAC numbering of the substrate, identify the α-carbon and the β-carbon. (Strong bases other than ethoxide have been included.)

1) $CH_3-CH_2-CHCl-CH_3 + OH^-K^+$

2) $CH_2Br-CH_2-CH_3 + CH_3O^-Na^+$

3) $(CH_3)_3-C-CHCl-CH_3 + CH_3CH_2O^-Li^+$

4) $CH_2Br-CH_2-CH_2-CH_3 + CH_3COO^-Na^+$

B. Give the major product in the following E1 reactions taking place with heat, if an E1 reaction is possible. (E2 may be favoured in some situations; answers these as E1.)

1) $CH_2Cl-CH(CH_3)-CH_2-CH_3$
      $+ OH^-Li^+$

2) $CH_3-CBr(CH_3)-C(CH_3)_2-CH_3$
      $+ CN^-K^+$

3) $CH_3-CH_2-CHI-CH(CH_3)-CH_3$
      $+ CH_3COO^-Na^+$

4) $CH_3-CH_2-CCl(CH_3)-CH_2-CH_3$
      $+ (F^-)_2Ca^{++}$

5) $CH_3-CH_2-C(CH_3)(OH)-CH(CH_3)_2$
      $+ H_3PO_4$

6) $CH_3-C(CH_2-CH_3)_2-OH$
      $+ H_2SO_4$

C. Use the expanded guidelines on page 3 to predict the major products for the following reactions. Identify which of the four kinds of reactions (E1, E2, S_N1, S_N2) is most favoured.

1) $CH_3-CH(CH_2-CH_3)-CH_2-CH_2-CH_2Br + CH_3-OH$

2) $CH_3-CH_2-C(CH_3)_2-OH + H_2SO_4$

3) $(CH_3)_2-CBr-CH_2-CH_3 + CH_3CHO^-Li^+$

4) $CH_3-CH(Cl)-CH_2-CH_3 + OH^-K^+$

5) $CH_3-CH_2-CH_2-C(CH_3)(I)-CH_2-CH_2-CH_3 + F^-Na^+$

SOLUTIONS

A: (1) $CH_3-CH=CH-CH_3$; α = C2, β = C3   (2) $CH_2=CH_2-CH_3$; α = C1, β = C2
(3) $(CH_3)_3-C-CH=CH_2$; α = C3, β = C4   (4) not E2; acetate is too weak
B: (1) not E1; α-carbon is primary   (2) $CH_2=C(CH_3)-C(CH_3)_2-CH_3$
(3) $CH_3-CH_2-CH=C(CH_3)-CH_3$ (4) $CH_3-CH=C(CH_3)-CH_2-CH_3$ (molecule is symmetric)
(5) $CH_3-CH_2-C(CH_3)=C(CH_3)_2$ (6) $CH_3-CH=C(CH_3)-CH_2-CH_3$
C: (1) $CH_3-CH(CH_2-CH_3)-CH_2-CH_2-CH_2-O-CH_3$; S_N2
      (2) $CH_3-CH=C(CH_3)_2$; E1
      (3) $(CH_3)_2-C=CH-CH_3$; E2
      (4) $CH_3-CH=CH-CH_3$; E2
      (5) either $CH_3-CH_2-CH_2-C(CH_3)(F)-CH_2-CH_2-CH_3$; S_N1; or
$CH_3-CH_2-CH=C(CH_3)-CH_2-CH_2-CH_3$; E1