**Thermodynamics and Kinetics in organic reaction**

If we consider a reaction in which Y is converted to Z, the thermodynamics of the reaction tells us the relative amounts of Y and Z that are present when the reaction has reached equilibrium, whereas the kinetics of the reaction tells us how fast Y is converted into Z.

$$Y \rightleftharpoons Z$$

The **mechanism** of a reaction describes the various steps that are believed to occur as reactants are converted into products. A reaction coordinate diagram shows the energy changes that take place in each of the steps of the mechanism.

Example : The reaction of A—B with C to form A and B—C.
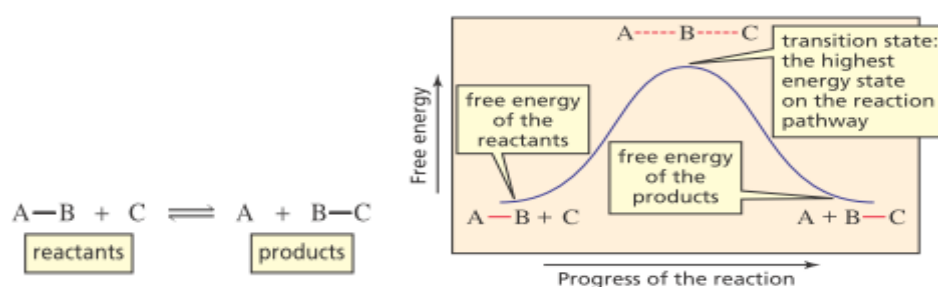
As the reactants are converted into products, the reaction passes through a maximum energy state called a **transition state.** The structure of the transition state lies somewhere between the structure of the reactants and the structure of the products. Bonds that break and bonds that form, as reactants are converted to products, are partially broken and partially formed in the transition state. Dashed lines are used to show partially broken or partially formed bonds. Transition states are shown in brackets with a double-dagger superscript.

Thermodynamics

The field of chemistry that describes the properties of a system at equilibrium is called
thermodynamics. For example :

$$m\,A + n\,B \rightleftharpoons s\,C + t\,D$$

$$K_{eq} = \frac{[\text{products}]}{[\text{reactants}]} = \frac{[C]^s\,[D]^t}{[A]^m\,[B]^n}$$

The relative concentrations of products and reactants at equilibrium depend on their relative stabilities: The more stable the compound, the greater is its concentration at equilibrium.

Several thermodynamic parameters are used to describe a reaction. The difference between the free energy of the products and the free energy of the reactants under standard conditions is called the **Gibbs free-energy change (ΔG^{o}).** The symbol ($^{\circ}$) indicates standard conditions—all species at a concentration of 1 M, a temperature of 25 C$^{\circ}$, and a pressure of 1 atm.

$$\Delta G° = \text{(free energy of the products)} - \text{(free energy of the reactants)}$$

From this equation, $\Delta G°$ will be negative if the products have a lower free energy (are more stable) than the reactants. In other words, the reaction will release more energy than it will consume. It will be an **exergonic reaction**. If the products have a higher free energy (are less stable) than the reactants, $\Delta G°$ will be positive, and the reaction will consume more energy than it will release; it will be an **endergonic reaction**. (Notice that the terms **exergonic** and **endergonic** refer to whether the reaction has a negative $\Delta G°$ or positive $\Delta G°$ respectively. Do not confuse these terms with **exothermic** and **endothermic**.

Therefore, whether reactants or products are favored at equilibrium can be indicated either by the equilibrium constant K_{eq} or by the change in free energy $\Delta G°$. These two quantities are related by the equation

$$\Delta G° = -RT \ln K_{eq}$$

where R is the gas constant (1.986×10^{-3} kcal mol^{-1} K^{-1}, or 8.314×10^{-3} kJ mol^{-1} K^{-1}, because 1 kcal = 4.184 kJ) and T is the temperature in degrees Kelvin

$$(K = °C + 273; \text{ therefore, } 25° C = 298 K).$$

$$\Delta G° = \Delta H° - T\Delta S°$$

The **enthalpy** term ($\Delta H°$) is the heat given off or the heat consumed during the course of a reaction. Atoms are held together by bonds. Heat is given off when bonds are formed, and heat is consumed when bonds are broken. Thus, ($\Delta H°$) is a measure of the bond-making and bond-breaking processes that occur as reactants are converted into products.

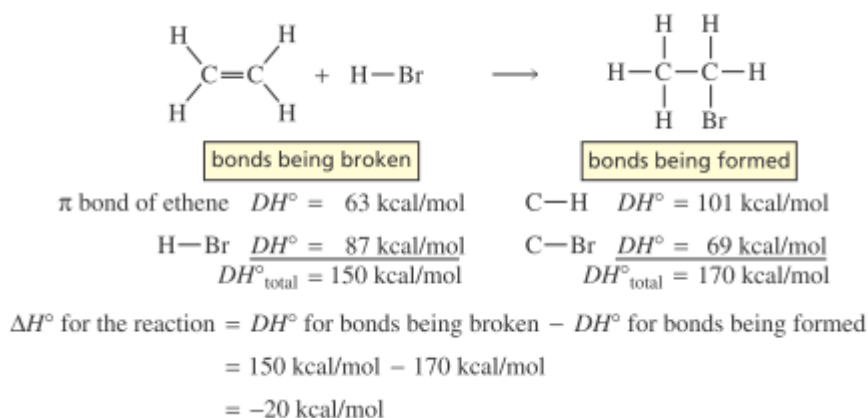$$\Delta H° = \text{(energy of the bonds being broken)} - \text{(energy of the bonds being formed)}$$

A reaction with a negative ($\Delta H°$) is called an exothermic reaction. If the bonds that are formed are weaker than those that are broken, ($\Delta H°$) will be positive. A reaction with a positive is called an endothermic reaction.

Entropy($\Delta S°$) is defined as the degree of disorder. It is a measure of the freedom of motion of the system. Restricting the freedom of motion of a molecule decreases its entropy. For example, in a reaction in which two molecules come together to form a single molecule, the entropy in the product will be less than the entropy in the reactants because two individual molecules can move in ways that are not possible when the two are bound together in a single molecule. In such a reaction ($\Delta S°$) will be negative. In a reaction in which a single molecule is cleaved into two separate molecules, the products will have greater freedom of motion than the reactant, and($\Delta S°$) will be positive.

$$\Delta S° = \text{(freedom of motion of the products)} - \text{(freedom of motion of the reactants)}$$

In other words, the formation of products with stronger bonds and with greater freedom of motion causes $\Delta G°$ to be negative.

Values of (ΔH^o) can be calculated from bond dissociation energies for example, the (ΔH^o) for the addition of HBr to ethene is calculated as shown here:

ΔH^o for the reaction = DH^o for bonds being broken − DH^o for bonds being formed

= 150 kcal/mol − 170 kcal/mol

= −20 kcal/mol

Kinetics

Knowing whether a given reaction is exergonic or endergonic will not tell you how fast the reaction occurs, because the ΔG^o of a reaction tells you only the difference between the stability of the reactants and the stability of the products; it does not tell you anything about the energy barrier of the reaction, which is the energy "hill" that must be climbed for the reactants to be converted into products. The higher the energy barrier, the slower is the reaction.

Kinetics is the field of chemistry that studies the rates of chemical reactions and the factors that affect those rates.

The energy barrier of a reaction, by $\Delta G^{\ddagger}$ is called the free energy of activation. It is the difference between the free energy of the transition state and the free energy of the reactants:

$$\Delta G^{\ddagger} = \text{(free energy of the transition state)} - \text{(free energy of the reactants)}$$

The smaller the $\Delta G^{\ddagger}$ the faster is the reaction. Thus, anything that destabilizes the reactant or stabilizes the transition state will make the reaction go faster.

Like ΔG^o , $\Delta G^{\ddagger}$ has both an enthalpy component and an entropy component. Notice that any quantity that refers to the transition state is represented by the double-dagger superscript($\ddagger$)

$$\Delta G^{\ddagger} = \Delta H^{\ddagger} - T\Delta S^{\ddagger}$$
$$\Delta H^{\ddagger} = \text{(enthalpy of the transition state)} - \text{(enthalpy of the reactants)}$$
$$\Delta S^{\ddagger} = \text{(entropy of the transition state)} - \text{(entropy of the reactants)}$$

Notice that ΔG^o relates to the equilibrium constant of the reaction, whereas $\Delta G^{\ddagger}$ relates to the rate of the reaction. The thermodynamic stability of a compound is indicated by ΔG^o .If ΔG^o is negative, for example, the product is thermodynamically stable compared with the reactant, and ΔG^o if is positive, the product is thermodynamically

unstable compared with the reactant. The kinetic stability of a compound is indicated by $\Delta G^{\ddagger}$. If $\Delta G^{\ddagger}$ for a reaction is large, the compound is kinetically stable because it does not undergo that reaction rapidly. If $\Delta G^{\ddagger}$ is small, the compound is kinetically unstable—it undergoes the reaction rapidly. Generally, when chemists use the term "**stability**," they are referring to thermodynamic stability.

Reaction Coordinate Diagram for the Addition of HBr to 2-Butene

The addition of HBr to 2-butene is a two-step reaction .The structure of the transition state for each of the steps is shown below in brackets. Notice that the bonds that break and the bonds that form during the course of the reaction are partially broken and partially formed in the transition state indicated by dashed lines. Similarly, atoms that either become charged or lose their charge during the course of the reaction are partially charged in the transition state. Transition states are shown in brackets with a double-dagger superscript.
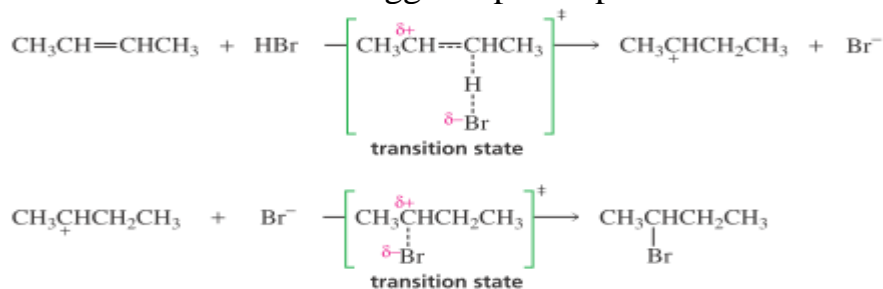

In the first step of the reaction, the alkene is converted into a carbocation that is less stable than the reactants. The first step, therefore, is endergonic ΔG^{o} is positive). In the second step of the reaction, the carbocation reacts with a nucleophile to form a product that is more stable than the carbocation reactant. This step, therefore, is exergonic ΔG^{o} is negative).
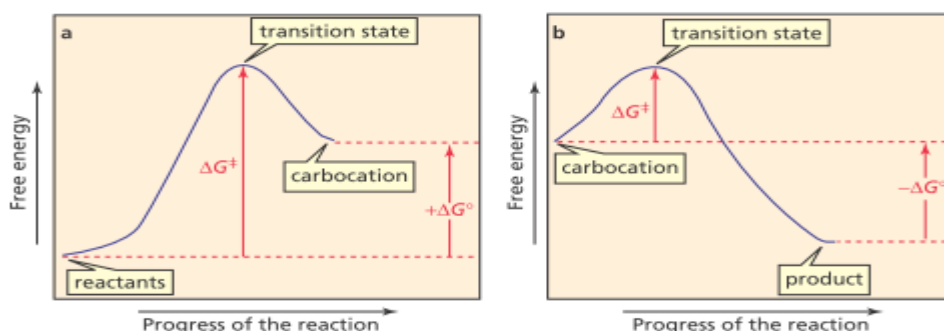
Because the product of the first step is the reactant in the second step, we can hook the two reaction coordinate diagrams together to obtain the reaction coordinate diagram for the overall reaction .The ΔG^{o} for the overall reaction is the difference between the free energy of the final products and the free energy of the initial reactants. The figure shows that

ΔG° for the overall reaction is negative. Therefore, the overall reaction is exergonic.
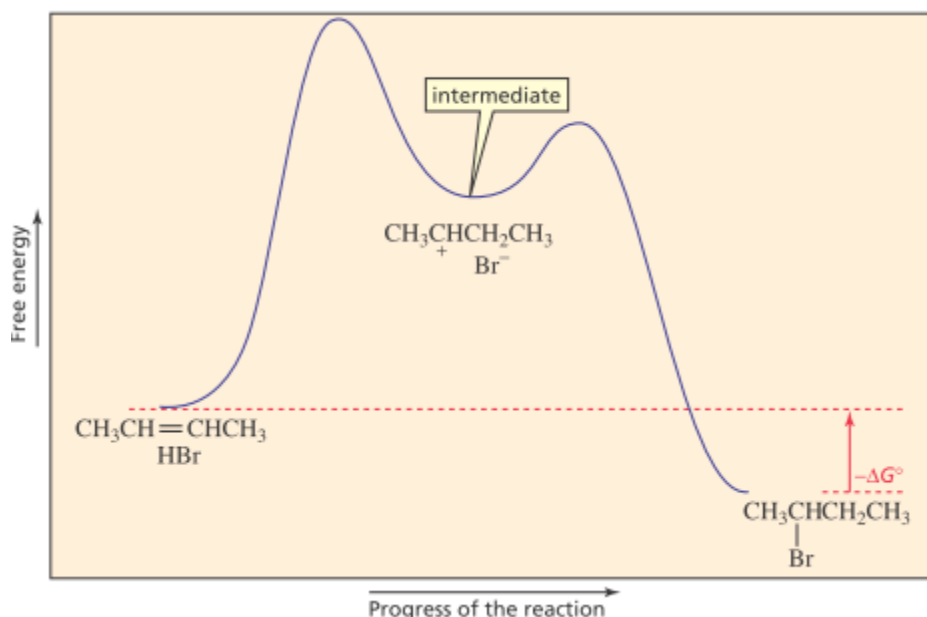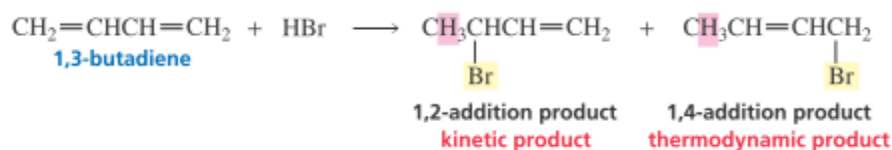

A chemical species that is the product of one step of a reaction and is the reactant for the next step is called an **intermediate**. The carbocation intermediate in this reaction is too unstable to be isolated, but some reactions have more stable intermediates that can be isolated. Transition states, in contrast, represent the highest-energy structures that are involved in the reaction. They exist only fleetingly and can never be isolated. Do not confuse transition states with intermediates: Transition states have partially formed bonds, whereas intermediates have fully formed bonds. The reaction step that has its transition state at the highest point on the reaction coordinate is called the rate-determining step or rate-limiting step. The rate determining step controls the overall rate of the reaction because the overall rate cannot exceed the rate of the rate-determining step.

Thermodynamic Versus Kinetic Control of Reactions
When a reaction produces more than one product, the product that is formed most rapidly is called the **kinetic product**, and the most stable product is called the **thermodynamic** product. Reactions that produce the kinetic product as the major product are said to be kinetically controlled. Reactions that produce the thermodynamic product as the major product are said to be thermodynamically controlled.
For many organic reactions, the most stable product is the one that is formed most rapidly. In other words, the kinetic product and the thermodynamic product are one and the same. Electrophilic addition to 1,3-butadiene is an example of a reaction in which the kinetic product and the thermodynamic product are not the same: The 1,2-addition

product is the kinetic product, and the 1,4-addition product is the thermodynamic product.

$$CH_2=CHCH=CH_2 + HBr \longrightarrow CH_3CHCH=CH_2 + CH_3CH=CHCH_2$$

1,3-butadiene

1,2-addition product
kinetic product

1,4-addition product
thermodynamic product

For a reaction in which the kinetic and thermodynamic products are not the same, the product that predominates depends on the conditions under which the reaction is carried out. If the reaction is carried out under sufficiently mild (low-temperature) conditions to cause the reaction to be irreversible, the major product will be the kinetic product. For example, when addition of HBr to 1,3-butadiene is carried out at (-80 °C) the major product is the 1,2-addition product 80% .

If, on the other hand, the reaction is carried out under sufficiently vigorous (high temperature) conditions to cause the reaction to be reversible, the major product will be the thermodynamic product. When the same reaction is carried out at 45 °C, the major product is the 1,4-addition product. Thus, the 1,2-addition product is the kinetic product (it is formed more rapidly), and the 1,4-addition product is the thermodynamic product (it is the more stable product).Why?

$$CH_2=CHCH=CH_2 + HBr \xrightarrow{45\ °C} CH_3CHCH=CH_2 + CH_3CH=CHCH_2$$

1,2-addition product
15%

1,4-addition product
85%
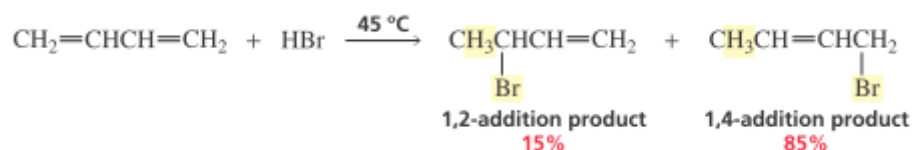
The first step of the addition reaction—addition of a proton to C-1—is the same whether the 1,2-addition product or the 1,4-addition product is being formed. It is the second step of the reaction that determines whether the nucleophile (Br⁻)attacks C-2 or C-4. Because the 1,2-addition product is formed more rapidly, we know that the transition state for its formation is
more stable (low energy barriers) than the transition state for formation of the 1,4-addition product(large energy barriers).

At low temperatures (-80 °C) there is enough energy for the reactants to overcome the energy barrier for the first step of the reaction and therefore form the intermediate, and there is enough energy for the intermediate to form the two addition products.

However, there is not enough energy for the reverse reaction to occur: The products cannot overcome the large energy barriers separating them from the intermediate. Consequently, at the relative amounts of the two products obtained reflect the relative energy barriers to the second step of the reaction. The energy barrier to formation of the 1,2-

addition product is lower than the energy barrier to formation of the 1,4-addition product, so the major product is the 1,2-addition product.

In contrast, at 45 °C, there is enough energy for one or more of the products to go back to the intermediate. The intermediate is called a **common intermediate** because it is an intermediate that both products have in common. The ability to return to a common intermediate allows the products to interconvert. Because the products can, interconvert, the relative amounts of the two products at equilibrium depend on their relative stabilities. The thermodynamic product reverses less readily because it has a higher energy barrier to the common intermediate, so it gradually comes to predominate in the product mixture.
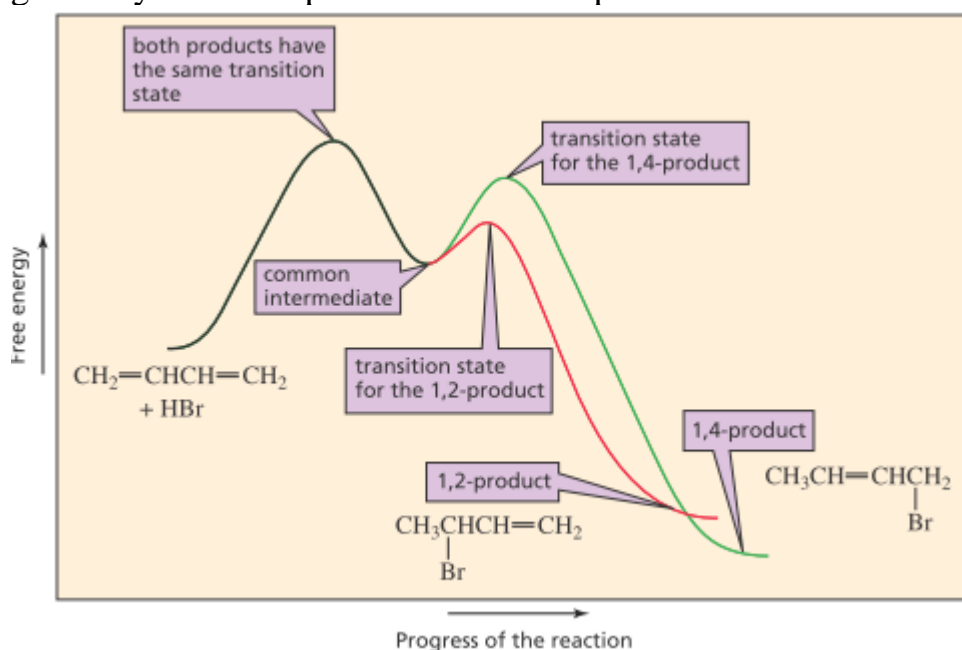
Thus, when a reaction is irreversible under the conditions employed in the experiment, it is said to be under kinetic control. When a reaction is under kinetic control, the relative amounts of the products depend on the rates at which they are formed.
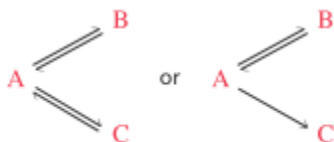

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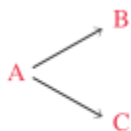
A reaction is said to be under thermodynamic control when there is sufficient energy to allow it to be reversible. When a reaction is under thermodynamic control, the relative amounts of the products depend on

their stabilities. Because a reaction must be reversible to be under thermodynamic control, thermodynamic control is also called equilibrium control.

For each reaction that is irreversible under mild conditions and reversible under more vigorous conditions, there is a temperature at which the changeover happens, depends on the reactants involved in the reaction. such as (45 °C) for the above example, even though addition of HBr to 1,3-butadiene is under thermodynamic control at that temperature C-Br is weaker than C-Cl requires less energy to undergo reverse reaction.

It is easy to understand why the 1,4-addition product is the thermodynamic product. Because the relative stability of an alkene is determined by the number of alkyl groups bonded to its sp2 carbons: The greater the number of alkyl groups, the more stable is the alkene. The two products formed from the reaction of 1,3-butadiene with one equivalent of HBr have different stabilities since the 1,2-addition product has one alkyl group bonded to its sp2 carbons, whereas the 1,4-product has two alkyl groups bonded to its sp2 carbons. The 1,4-addition product, therefore, is more stable than the 1,2-addition product. Thus, the 1,4-addition product is the thermodynamic product.

$$CH_3CHCH=CH_2 \qquad CH_3CH=CHCH_2$$
$$| \qquad\qquad\qquad\qquad |$$
$$Br \qquad\qquad\qquad\qquad Br$$
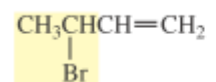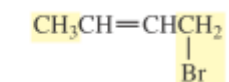
1,2-addition product   1,4-addition product
kinetic product   thermodynamic product

Why the 1,2-addition product is formed faster? In other words, why is the transition state for formation of the 1,2-addition product more stable than the transition state for formation of the 1,4-addition product? For many years, chemists thought it was because the transition state for formation of the 1,2-addition product resembles the contributing resonance structure in which the positive charge is on a secondary allylic carbon. In contrast, the transition state for formation of the 1,4-addition product resembles the contributing resonance structure in which the positive charge is on a less stable primary allylic carbon.
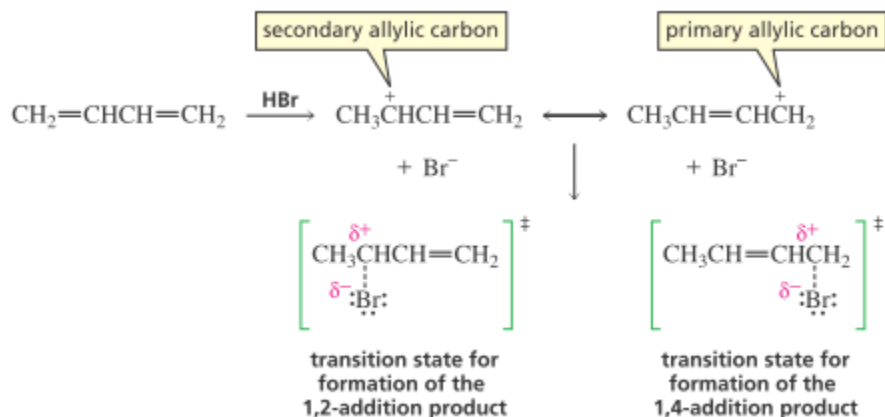
However, when the reaction of (1,3-pentadien + DCl) is carried out under kinetic control, essentially the same relative amounts of 1,2- and 1,4-addition products are obtained as are obtained from the kinetically controlled reaction of 1,3-butadien +HCl . The transition states for formation of the 1,2- and 1,4-addition products from 1,3-pentadiene should both have the same stability because both resemble a contributing resonance structure in which the positive charge is on a secondary allylic carbon. Why, then, is the 1,2-addition product still formed faster?
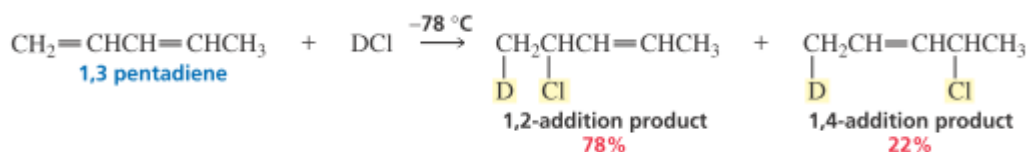
When the π electrons of the diene abstract D^+ from a molecule of undissociated DCl, the chloride ion can better stabilize the positive charge at C-2 than at C-4 simply because when the chloride ion is first produced, it is closer to C-2 than to C-4. So it is a proximity effect that causes the 1,2-addition product to be formed faster. A proximity effect is an effect caused by one species being close to another.
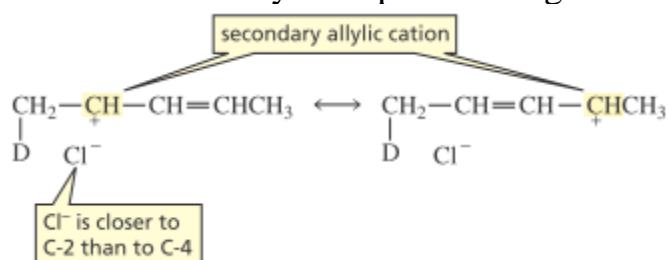
Because the greater proximity of the nucleophile to C-2 contributes to the faster rate of formation of the 1,2-addition product, the 1,2-addition product is the kinetic product for essentially all conjugated dienes. Do not assume, however, that the 1,4-addition product is always the thermodynamic product. The structure of the conjugated diene is what ultimately determines the thermodynamic product. For example, the 1,2-addition product is both the kinetic product and the thermodynamic

product in the reaction of 4-methyl-1,3-pentadiene with HBr, because not only is the 1,2-product formed faster, it is more stable than the 1,4-product.

$$CH_2{=}CHCH{=}\overset{\underset{\displaystyle |}{CH_3}}{C}CH_3 \ +\ HBr \ \longrightarrow$$

4-methyl-1,3-pentadiene

$$CH_3\overset{\underset{\displaystyle |}{}}{C}HCH{=}\overset{\underset{\displaystyle |}{CH_3}}{C}CH_3 \quad + \quad CH_3CH{=}\overset{\underset{\displaystyle |}{CH_3}}{C}H\overset{\underset{\displaystyle |}{}}{C}CH_3$$
$$\underset{Br}{|} \qquad\qquad\qquad \underset{Br}{|}$$

4-bromo-2-methyl-2-pentene   **4-bromo-4-methyl-2-pentene**
1,2-addition product   **1,4-addition product**
kinetic product
thermodynamic product
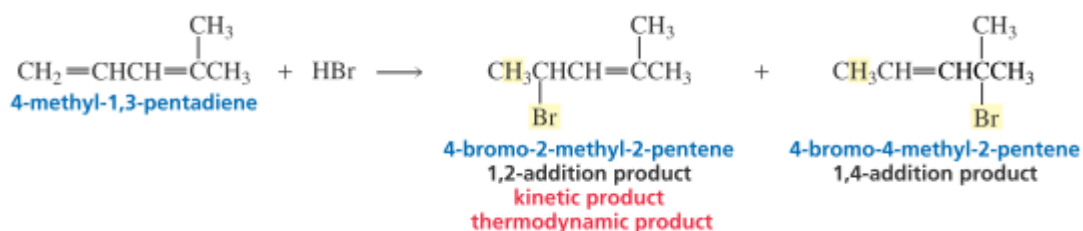
The 1,2- and 1,4- addition products obtained from the reaction of 2,4-hexadiene with HCl have the same stability—both have the same number of alkyl groups bonded to their sp2 carbons. Thus, neither product is themodynamically controlled.

$$CH_3CH{=}CHCH{=}CHCH_3 \xrightarrow{\ HCl\ } CH_3CH_2\overset{\underset{\displaystyle |}{}}{C}HCH{=}CHCH_3 \quad + \quad CH_3CH_2CH{=}CH\overset{\underset{\displaystyle |}{}}{C}HCH_3$$
$$\qquad\qquad\qquad\qquad\qquad\qquad \underset{Cl}{|} \qquad\qquad\qquad\qquad\qquad \underset{Cl}{|}$$

2,4-hexadiene   **4-chloro-2-hexene**   **2-chloro-3-hexene**
               1,2-addition product   **1,4-addition product**

the products have the same stability
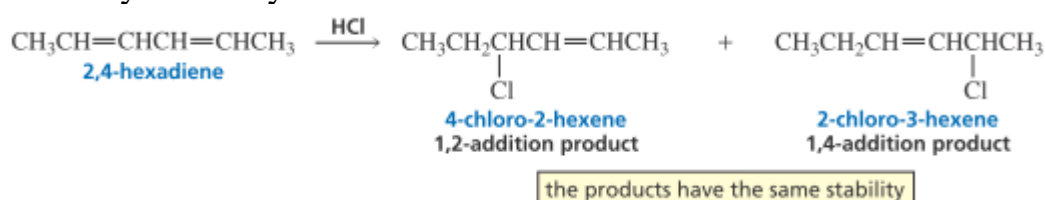
Q/

For each of the following reactions, (1) give the major 1,2- and 1,4-addition products and (2) indicate which is the kinetic product and which is the thermodynamic product:

a.

$+$ HCl $\longrightarrow$

c.

$+$ HCl $\longrightarrow$

b. $CH_3CH{=}CHC{=}CH_2 \ +\ HCl \ \longrightarrow$
$$\qquad\qquad\quad \underset{CH_3}{|}$$

d.

$+$ HCl $\longrightarrow$