

ChemActivity 14

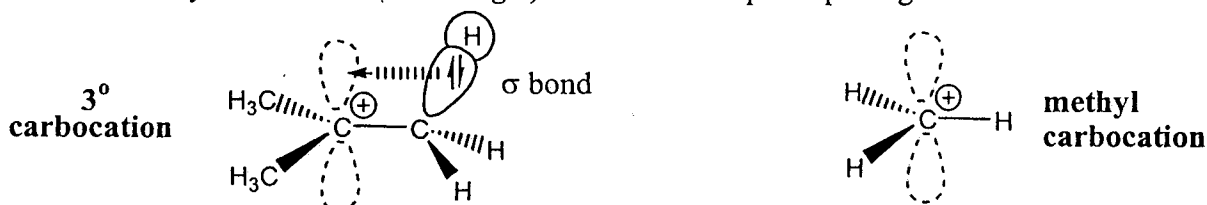
Part A: Two-Step Elimination

(By what mechanism do carbocations easily become alkenes?)

Model 1: Hyperconjugation ("Weak Conjugation")

In the 3° carbocation (*below left*) one C—H σ bond is shown as an overlap of orbitals. The electron pair in this C—H bond donates some of its electron density into the empty p orbital, helping to complete the octet of the carbocation carbon. This weak orbital overlap is sometimes called **hyperconjugation**. For a 3° carbocation this effect is multiplied $\times 9$ (since all nine C—H bonds do this). This explains why alkyl groups are electron donating and tertiary carbocations are relatively stable.

The methyl carbocation (*below right*) has no such help completing its octet.

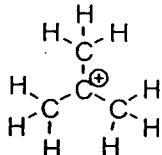


Critical Thinking Questions

1. Consider the C—H σ bond in Model 1 shown as an overlap of orbitals. Do you expect the presence of the empty p orbital to strengthen or weaken this C—H bond? Explain your reasoning.

overlows empty p orbital
Lower e⁻ density of σ bond & weakens it.

2. Is your answer in CTQ 1 consistent with the following pK_a ? Which H does this pK_a refer to?

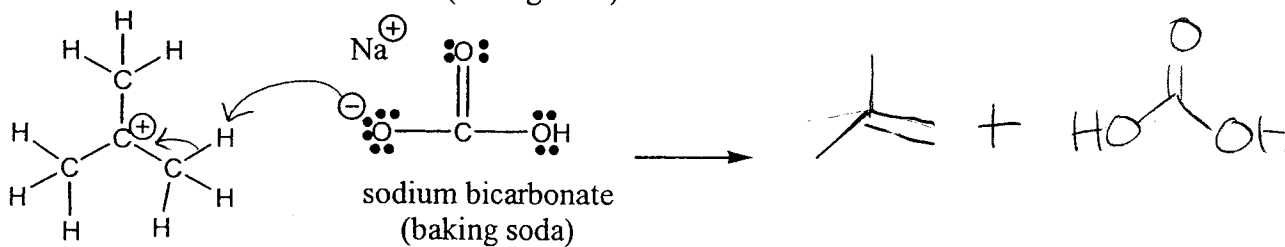


strong acid

yes

Any one of the H's

3. A tertiary carbocation is such a strong acid that it will react with a very weak base such as sodium bicarbonate (baking soda).



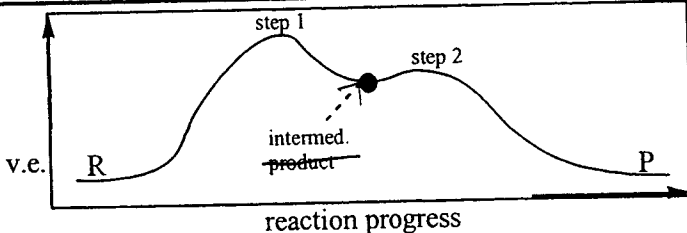
weak base & poor nucleophile

- a) Show the mechanism and the products of this acid-base reaction.

Model 2: Two-Step Elimination

Table 2: Concentration Dependence of Reaction Rate for Two-Step Elim.

[R—Br]	[HCO ₃ ⁻] (baking soda)	Rel. Rxn. Rate
1 M	1 M	1
2 M	1 M	2
1 M	2 M	1



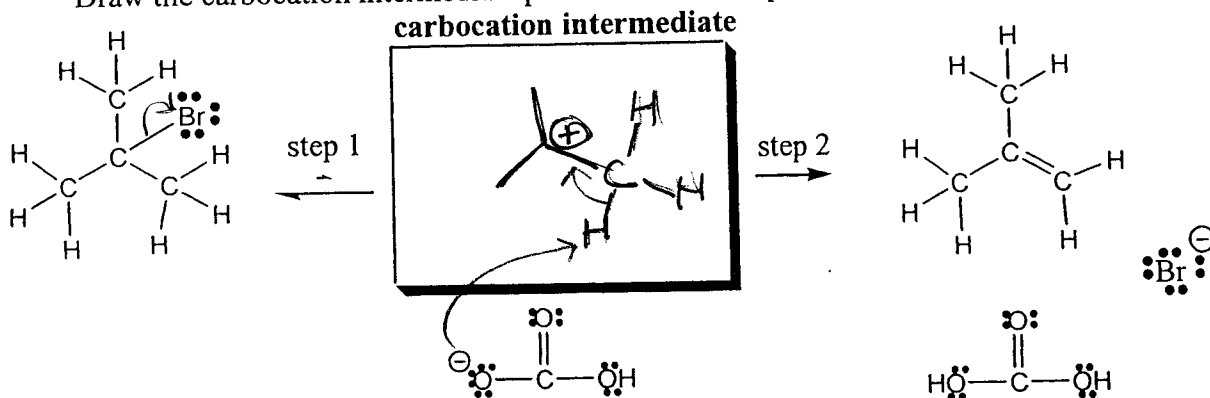
Elimination = formation of a π bond via removal of a leaving group and proton.

Critical Thinking Questions

4. Based on the information in Table 2:

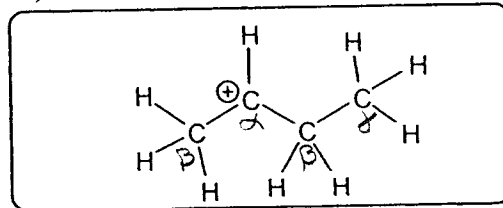
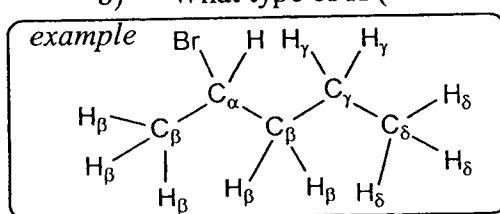
- a) Is baking soda involved in the slowest step of this reaction? Explain how you can tell. **NO b/c the rxn rate does NOT change when the [HCO₃⁻] is changed**
- b) Which step is the slow step in this reaction? Explain how you can tell. **ionization of R-Br b/c the rxn rate changes when the [R-Br] is changed.**

5. Use curved arrows to show the mechanism of this two-step elimination reaction. Draw the carbocation intermediate product in the box provided.



6. Chemists use the Greek letters α, β, δ , etc. to designate how far away a C atom is from a functional group such as Br. H's attached to a C _{α} are called α -H's, H's attached to a C _{β} are called β -H's, etc. (See the example below left).

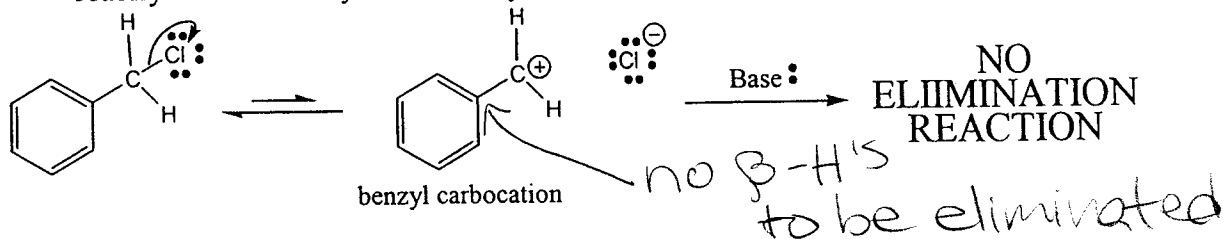
- a) Label the C's and H's in the example at right with α, β, γ , etc., as appropriate.
- b) What type of H (which Greek letter) can be eliminated by the base?



c) Draw the three possible alkene products produced if a base reacts with the carbocation in the right hand box. (Hint: two of them are *cis/trans* isomers.)



7. Explain why the following molecule cannot undergo elimination, even though it readily forms the very stable benzyl carbocation shown. (Hint: review CTQ 6.)



Part B: One-Step Elimination

(What reaction conditions favor elimination over substitution?)

Model 3: One-Step Elimination

Table 3a: Concentration Dependence of Reaction Rate for One-Step Elim.

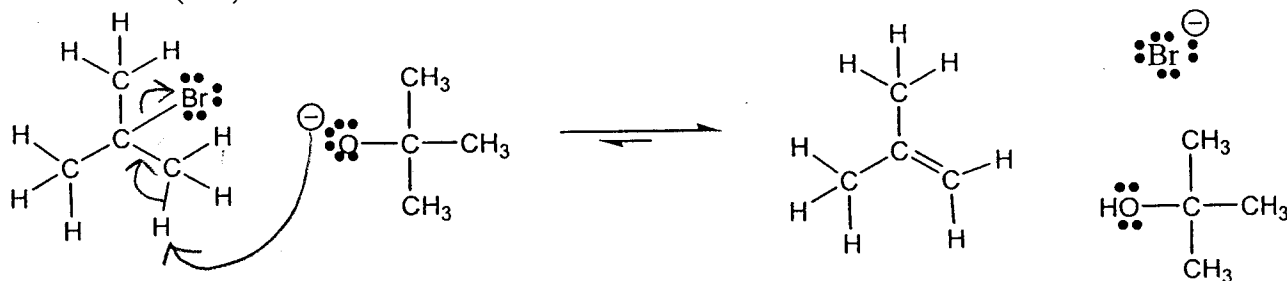
[R—X]	Tert-butoxide (base)	Relative Rxn. Rate
1 M	1 M	1
2 M	1 M	2
1 M	2 M	2
2 M	2 M	4

Critical Thinking Questions

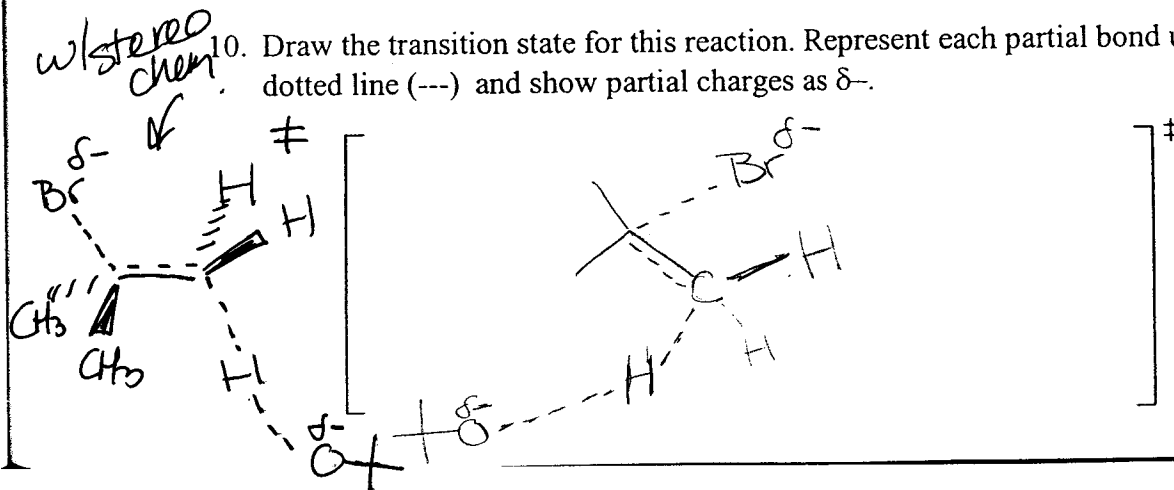
8. Explain how the data in Model 3 show that this reaction happens in a single step.

The rxn rate changes when both the [R-X] &/or [EtO⁻] are changed

9. Use curved arrows to show a mechanism of this reaction that is consistent with the kinetic (rate) data and the reaction energy diagram shown in Model 3.



10. Draw the transition state for this reaction. Represent each partial bond using a dotted line (---) and show partial charges as δ^- .



11. The book calls...

a **one-step** elimination reaction an "E2 reaction," and
a **two-step** elimination reaction an "E1 reaction."

The "E" stands for "elimination," but the 1 and 2 seem to be backwards. To what are the "1" and "2" referring?

E2 = bimolecular transition state
E1 = unimolecular t.s.

12. Construct an explanation for why a weak base such as baking soda ($\text{Na}^+ \text{HCO}_3^-$) will not work as the base in an E2 reaction even though it is ok for an E1 reaction such as the one in CTQ 5. Since C^+ are very strong acids, a weak base like HCO_3^- can remove the $\beta\text{-H}$ in E1. The HCO_3^- is more stable than the LG^- , so no rxn occurs?

*ignoring equilibrium effects

13. If there is one thing that makes organic chemistry students go gray, it's the fact that many molecules will undergo more than one of the four reactions we have been discussing. In the laboratory, it is often impossible to avoid a mixture of substitution and elimination products. Fill in the following table to help sort out what molecules and conditions are likely to cleanly undergo only one of these mechanisms.

Table 3b: Conditions that Favor... (S_N1, S_N2, E1 or E2)

Favored Mech.	Base/Nuc	R-X	X (leaving group)	Rate dependent on concentration of	Solvent
S _N 1	weak base good Nu:	2°, 3°, allyl & benzyl only	excellent LG	R-X only	very poor protic
S _N 2	weak base good Nu.	Methyl are best 2° ok	good LG	R-X & Nu	polar is better but mildly polar ok
E1	weak base poor Nu	must have $\beta\text{-H}$ next to C^+ 2°, 3°, allyl & benzyl	excellent LG	R-X only	very polar protic
E2	strong base poor Nu	must have acidic $\beta\text{-H}$ to C-LG methyl will not react	good LG	R-X & base	polar is better but mildly polar is okay

Fill in the table above with the following phrases:

Col. 2: Strong base/poor nucleophile; Weak base/poor nucleophile; Weak base/good nucleophile (put this last phrase in two different boxes!)

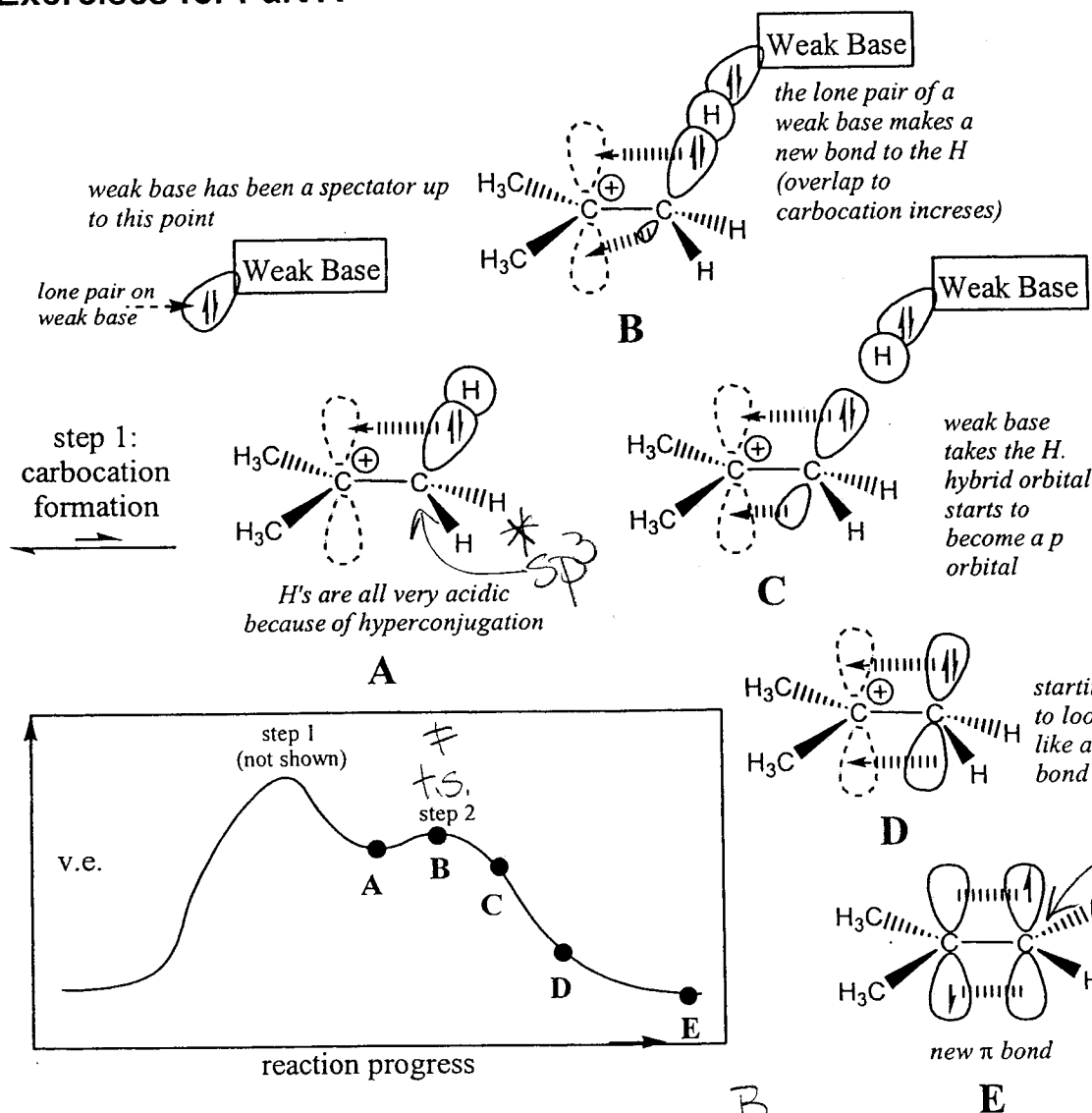
Col. 3: 2° and 3° allyl or benzyl only; 2°, 3° allyl or benzyl only AND must have $\beta\text{-H}$ to C^+ ; methyl and 1° best but 2° ok; must have acidic $\beta\text{-H}$ to C-LG , e.g. methyl will not do

Col. 4: excellent leaving group required (two boxes!); good leaving group (two boxes!)

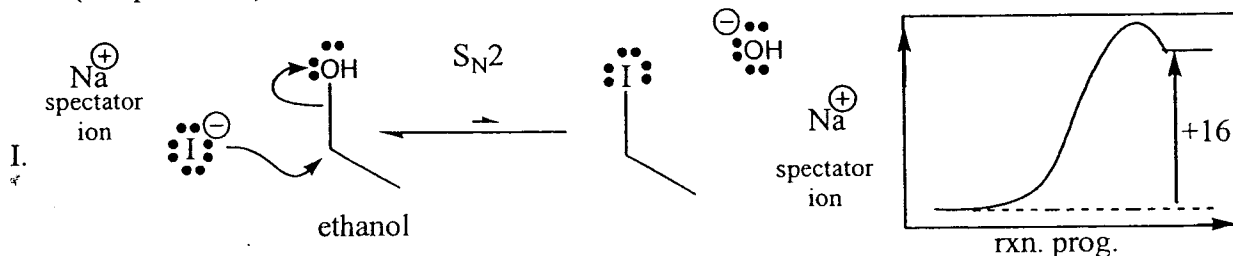
Col. 5: R-X only (two boxes!); R-X and Base; R-X and Nucleophile

Col. 6: very polar, protic (two boxes!); polar is better but mildly polar is okay (two boxes!)

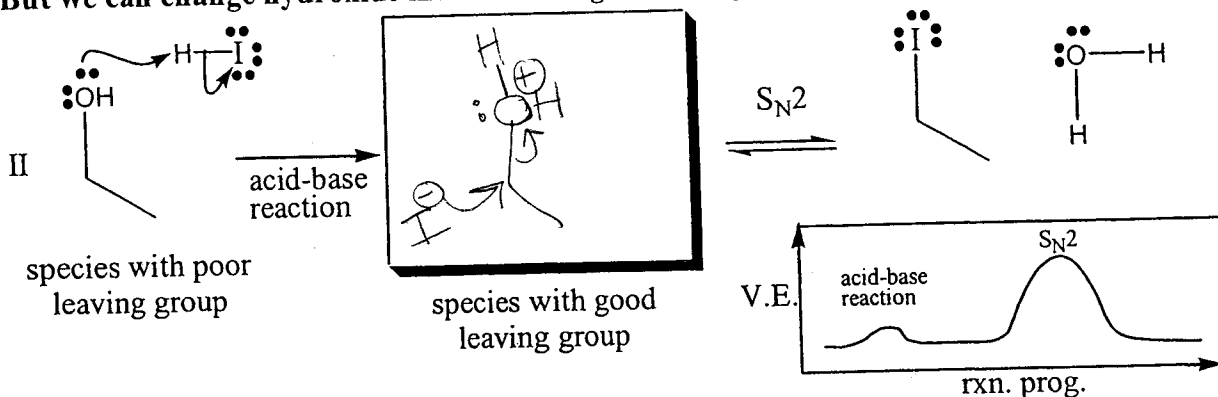
Exercises for Part A



- Which point (of A-E) is the transition state of step 2? Draw this transition state using dotted lines to represent partial bonds and δ 's to represent partial charges.
- One carbon involved in the reaction above changes hybridization state during the reaction. Label this C with its hybridization state in A (start) and in E (end).
- Hydroxide (OH^-) is a poor leaving group. This is because it takes so much energy ($\sim 16\text{pK}_a$ units) to break the $\text{C}-\text{OH}$ bond and set HO^- free. (See Q's on next page.)



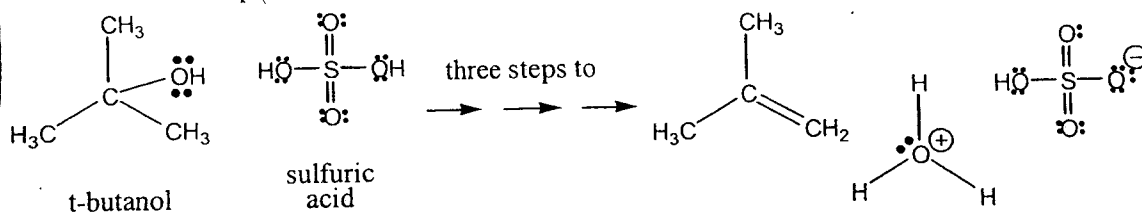
But we can change hydroxide into something that is a good leaving group!!



- In the box above, draw the products of the reaction shown with curved arrows (step 1 of Reaction II).
- Use curved arrows to show the S_N2 reaction in step 2 of Reaction II.
- Why is water (OH_2) a better leaving group than hydroxide (OH^-)?
H₂O has lower PE than OH⁻ H₂O is more stable than OH⁻

4. The products shown in Reaction II can also be achieved by mixing ethanol ($\text{CH}_3\text{CH}_2\text{OH}$) with sulfuric acid (H_2SO_4) and NaI. Use curved arrows to show the mechanism of this reaction. (Hint: the first step is an acid-base reaction.)

5. If t-butanol is mixed with sulfuric acid (and no nucleophile like I^- is introduced) the result is an acid-base reaction followed by a two-step elimination reaction. The reactants and products are shown below for this overall three step process. Use curved arrows to show the entire mechanism of this reaction and draw the two intermediate products. (Note that water is a stronger base than HSO_4^-)

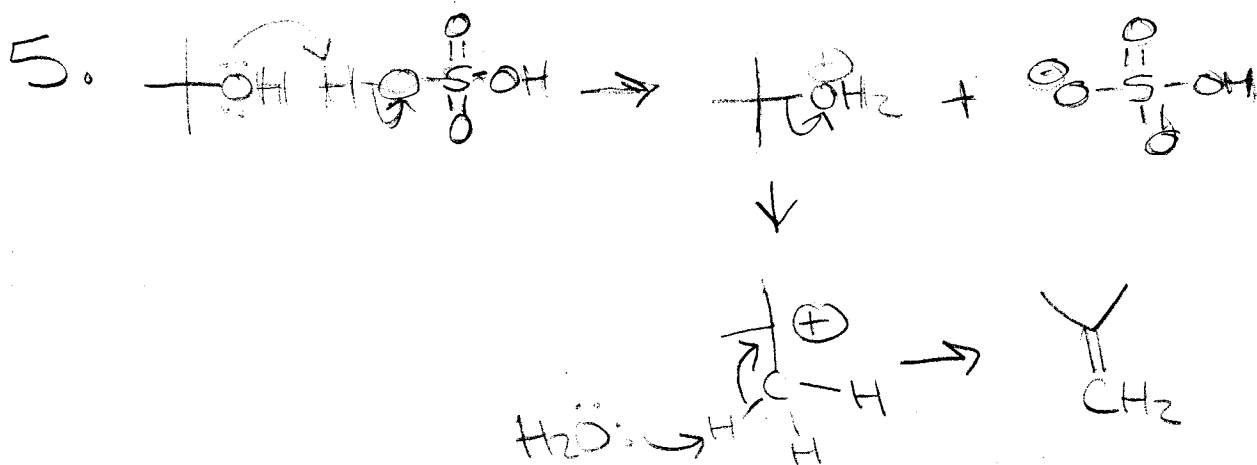
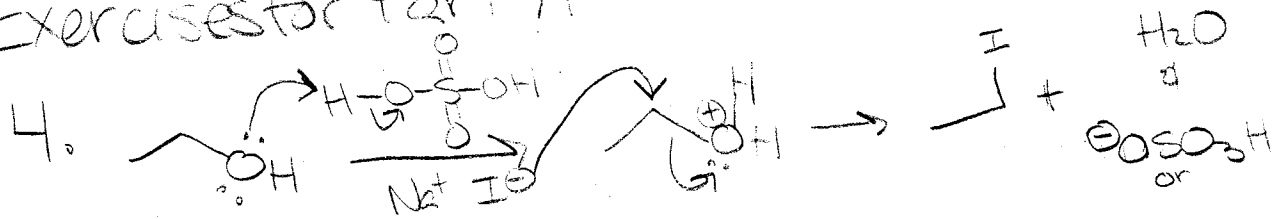


- A lab technician accidentally spills some sodium iodide into the reaction mixture in Exercise 5. (NaI dissociates into Na^+ and I^-). As a result a substitution product is observed along with the elimination product. Use curved arrows to show the mechanism of this side reaction and draw the substitution product. (Is this substitution likely to be an S_N1 or an S_N2 reaction?)
- If t-butanol in the reaction in Exercise 5 is replaced with 3-methyl-3-pentanol three different alkene products are produced. If it is replaced with 3-methyl-3-hexanol five different alkene products are produced. Draw all these products.

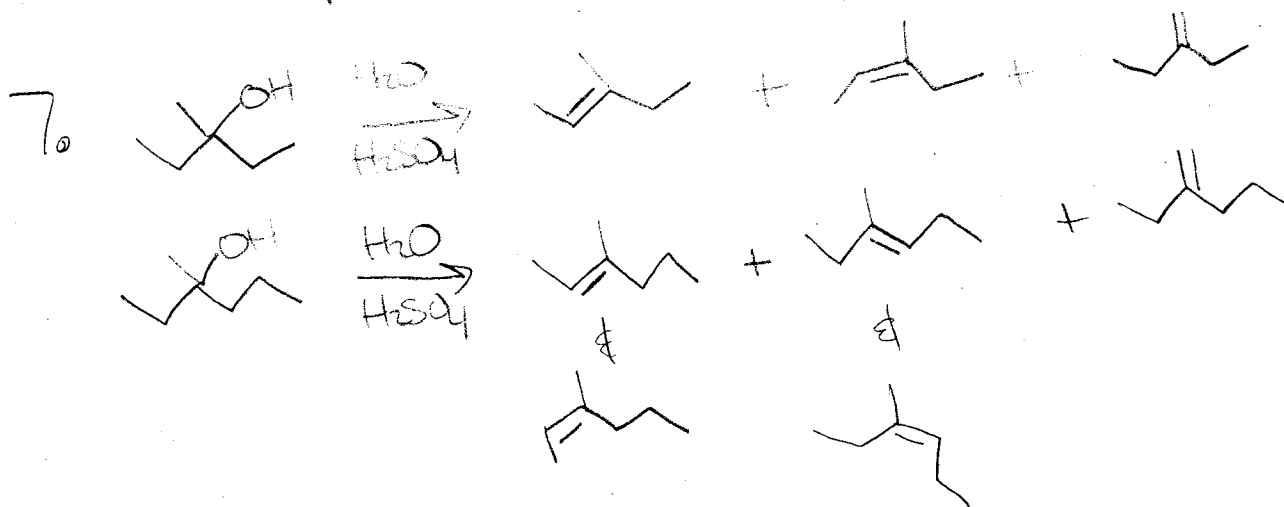
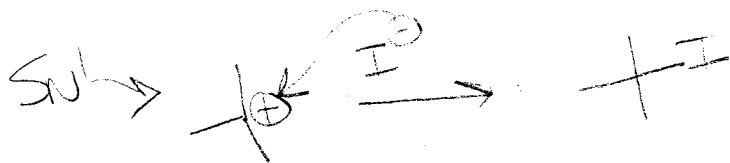
Chem Activity 14 Elimination Rxns

E1 & E2

Exercises for Part A



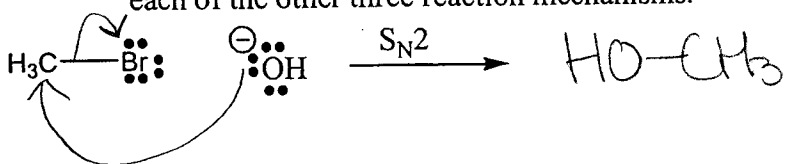
6. steps 1 & 2 above



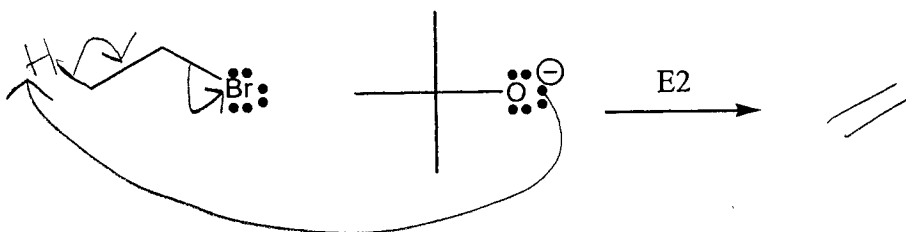
Exercises for Part B

9. Most substitution or elimination reactions are competitions between two or more of the four reaction mechanisms we have discussed. Each of the following reactions go almost exclusively by the mechanism written over the arrow. For each reaction...

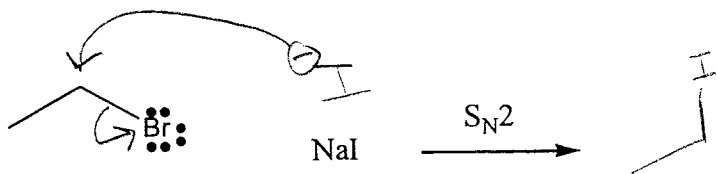
- Use curved arrows to show the mechanism and draw the product/s.
- Briefly explain why these starting materials can't or are unlikely to go by each of the other three reaction mechanisms.



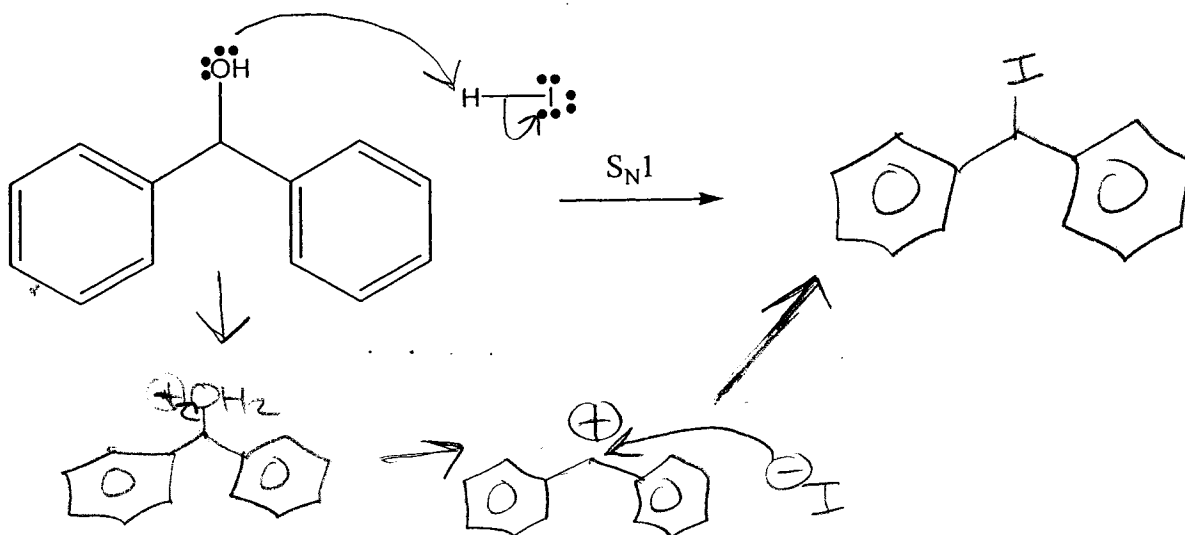
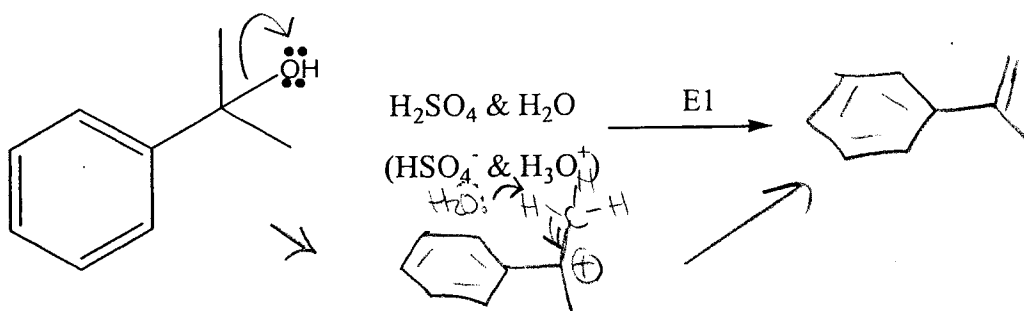
no E1 or E2
b/c no β -H
no S_N1 (& E1)
b/c methyl C^+ is
too unstable



strong
bulky
base



good Nu
&
weak base

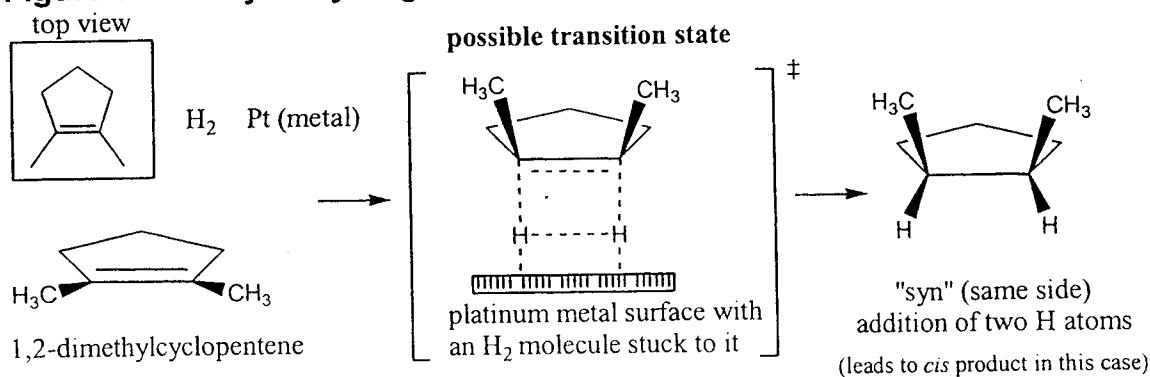
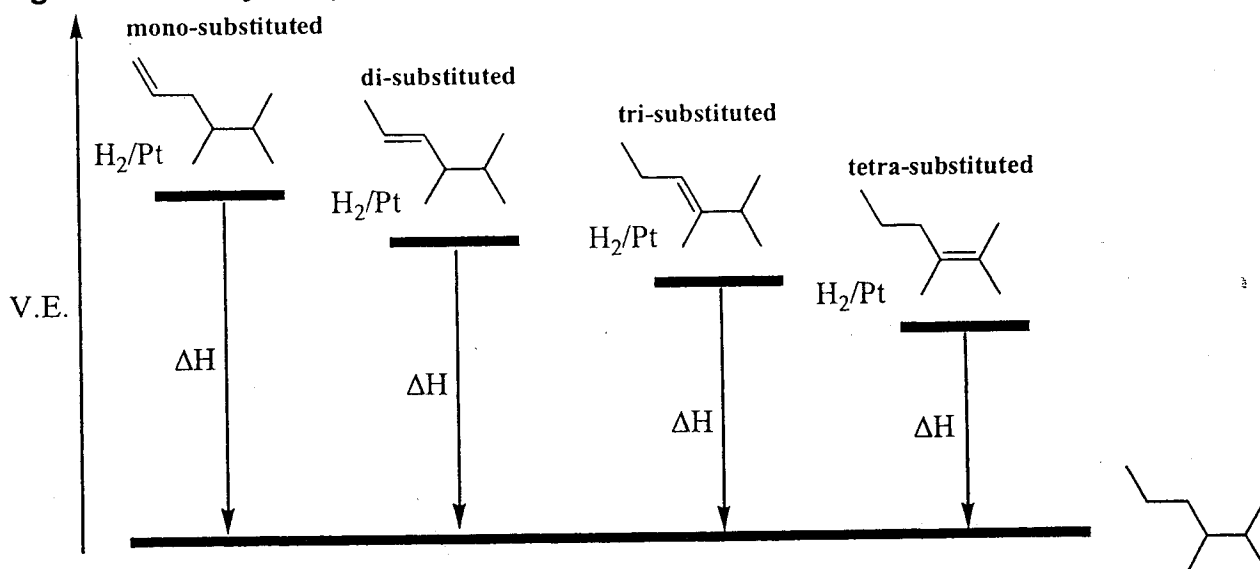


Key
SP 11ChemActivity 15**Part A: Alkene Potential Energy**

(What are the relative potential energies of substituted and unsubstituted double bonds?)

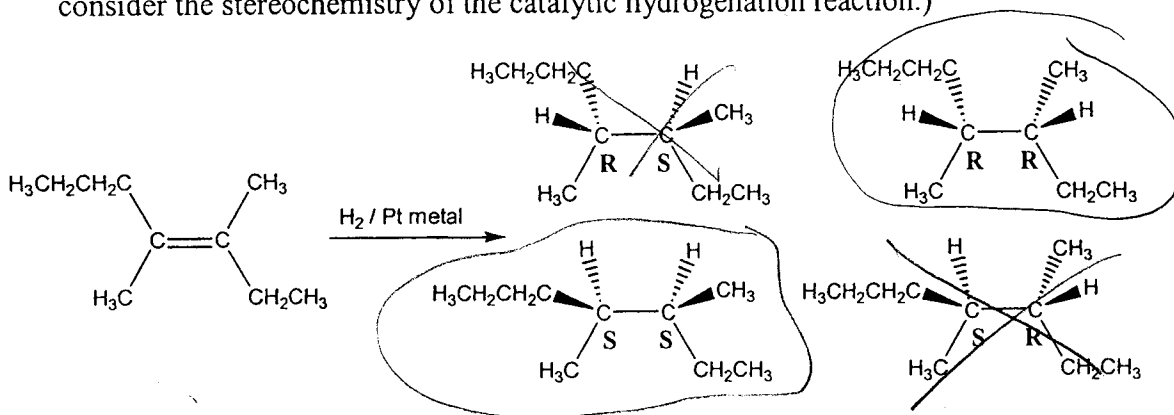
Model 1: Heats of Hydrogenation ($\Delta H_{\text{hydrogenation}}$)

$\Delta H_{\text{hydrogenation}}$ = heat released when two H atoms are added to a double bond. You do not need to know the mechanism of this reaction (called **catalytic hydrogenation**). Know only that the metal, usually platinum (Pt) or palladium (Pd) delivers two H atoms simultaneously to the **same side** of the double bond, as in Figure 1a (this is called "**syn addition**").

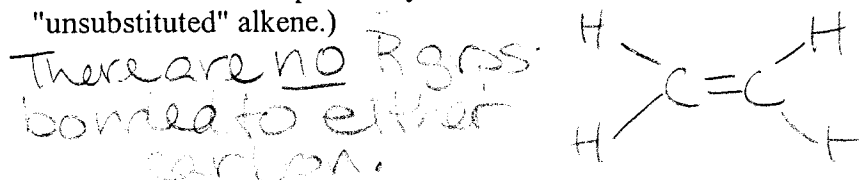
Figure 1a: Catalytic Hydrogenation of 1,2-dimethylcyclopentene**Figure 1b: Catalytic Hydrogenation of Various C_8H_{16} Constitutional Isomers****Critical Thinking Questions**

1. Is catalytic hydrogenation an exothermic or an endothermic [circle one] reaction?

2. For the following catalytic hydrogenation reaction, circle the two products that do form, cross out the two that do not form, and explain your reasoning. (Hint: consider the stereochemistry of the catalytic hydrogenation reaction.)



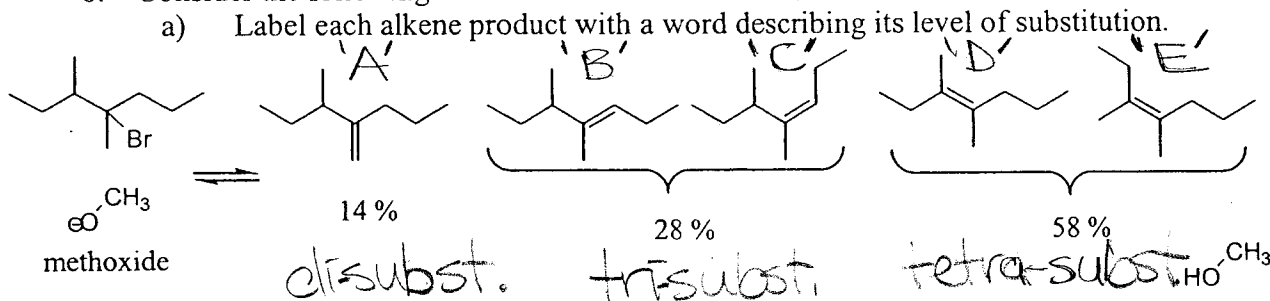
3. What do the labels **mono-substituted**, **di-substituted**, **tri-substituted** and **tetra-substituted** in Figure 1b refer to? *The # of R groups bonded to the 2 carbons forming the double bond.*
4. An **un-substituted** alkene has a molecular formula of C_2H_4 . Draw the structure of this molecule and explain why it is called **un-substituted**. (This is the only "unsubstituted" alkene.)



5. According to the information in Figure 1b, what is the relationship between the level of substitution of a double bond and the potential energy of the alkene?

The PE of the alkene ↓ as the level of substitution ↑.

6. Consider the following elimination reaction:



- b) Is your conclusion in CTQ 5 consistent with the product distribution shown above? Explain. *yes, the more stable products are synthesized in greater percentages*
- c) Explain why the words **cis** and **trans** are not adequate to describe the difference between the two tri-substituted products above.

Because we do not have enough information to determine the structure of the tri substituted alkene.

Model 2: E vs. Z (more general than *cis* vs. *trans*)

As you saw on the previous page, some molecules are too complex to be called simply *cis* or *trans*. For these molecules, the E vs. Z system was invented.

- For the two groups attached to each sp^2 carbon, assign one as larger and the other as smaller using the same rules you learned for assigning R and S.
- If the two larger groups are on the same side of the double bond (*cis*-like), the structure is called **Z**, for the German word *zusammen* meaning "together."
- If the two larger groups are on opposite sides of the double bond (*trans*-like), the structure is called **E**, for the German word *entgegen* meaning "opposite."

There are several good ways to remember the definitions of E and Z:

- Think Z for "zis-like."
- Think Z for "zee zame zide" (say it in a German accent).
- Think consonant with consonant, vowel with vowel: **Z**/Together **E**/Opposite

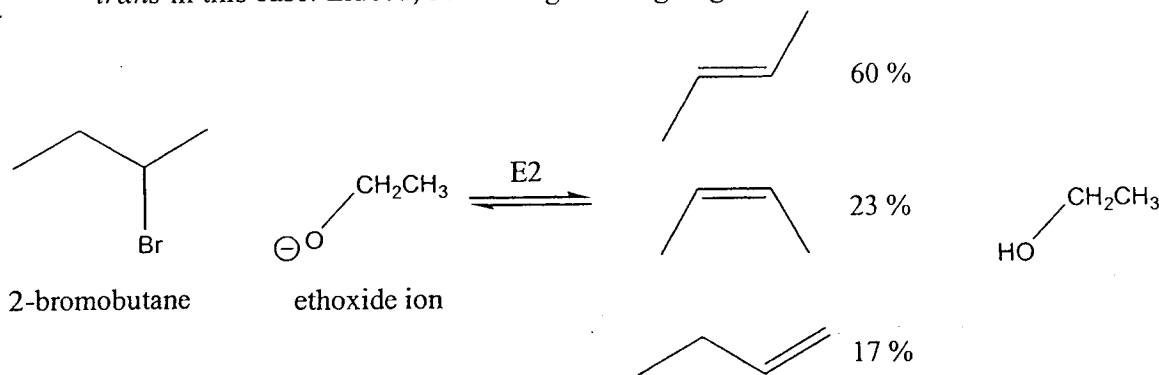
Critical Thinking Questions

7. E vs. Z applies to four of the products in CTQ 6. Assign these structures E or Z.
8. E vs. Z does not apply to one of the alkene products in CTQ 6. Explain why.

'A' = no E/Z b/c both substitutions are on the same carbon (NO *cis/trans* either)
 'B' = E 'C' = Z 'D' = E 'E' = Z

Model 3: A Closer Look at E2 Reaction Product Distributions

- Based simply on alkene potential energies you would predict that the mono-substituted alkene is the minor product of the E2 reaction below.
- And, in general, *trans* or E molecules are lower in potential energy than *cis* or Z molecules, but this difference is not enough to explain the large preference for *trans* in this case. Indeed, something else is going on!



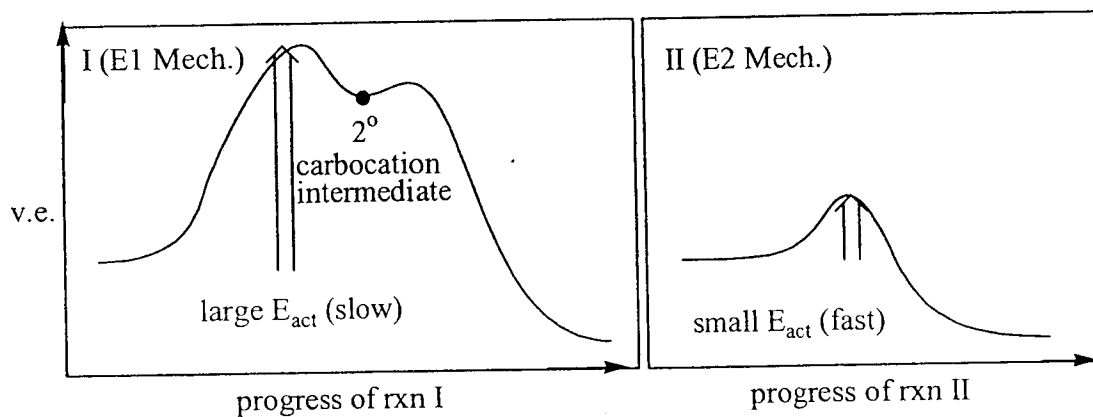
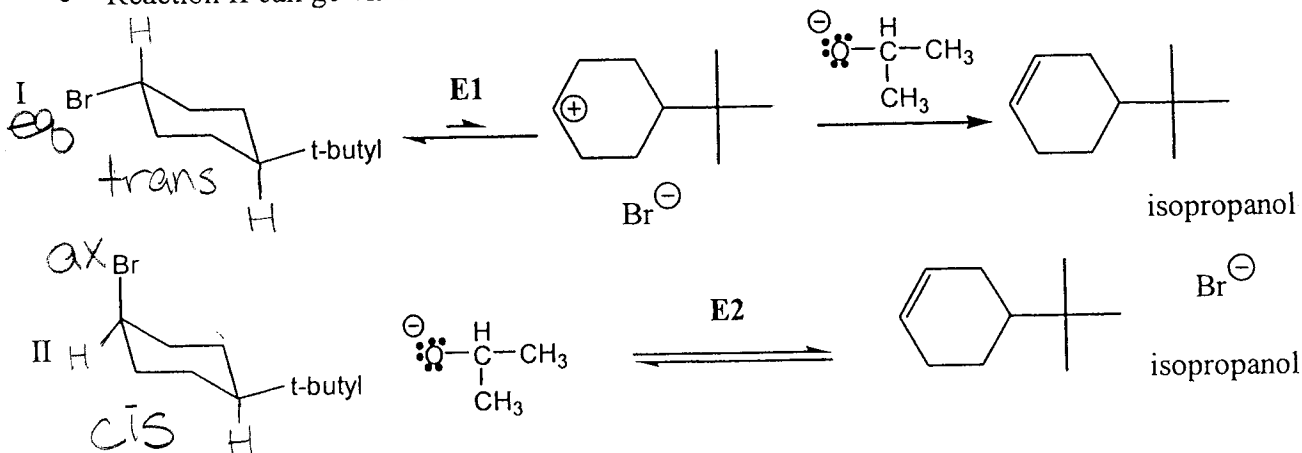
Critical Thinking Questions

9. Why are *trans* or E molecules usually lower in potential energy than *cis* or Z molecules. The transition state & products are lower in E b/c there is less steric hindrance*
10. According to Model 3, is the energy difference between *trans*-2-butene and *cis*-2-butene large enough to account for the product distribution shown above? yes

* between the "substituents"

Model 4: Leaving Group Position in an E2 Reaction

- Both reactions are run in a mildly polar solvent that does not support ions well.
- Reaction I, below, can ONLY go via a carbocation intermediate (E1 reaction).
- Reaction II can go via an E2 mechanism and is much faster in this solvent.



Critical Thinking Questions

- Why is an E1 mechanism much slower than an E2 mechanism in a mildly polar solvent? *It takes more energy to form the C^+ creating a larger E_a (slower rate).*
- Label one of the starting materials above *trans* and the other *cis*. (It may help to draw in the H's on C_1 and C_4 of the ring. *see above*)
 - Label each leaving group (Br) as being axial or equatorial in each. (Recall that the very large *tert*-butyl group "demands" the more roomy equatorial position.) *see above*
 - According to Model 4, an E2 mechanism is possible on a substituted cyclohexane ring when the leaving group is in an axial position or equatorial position [circle one].

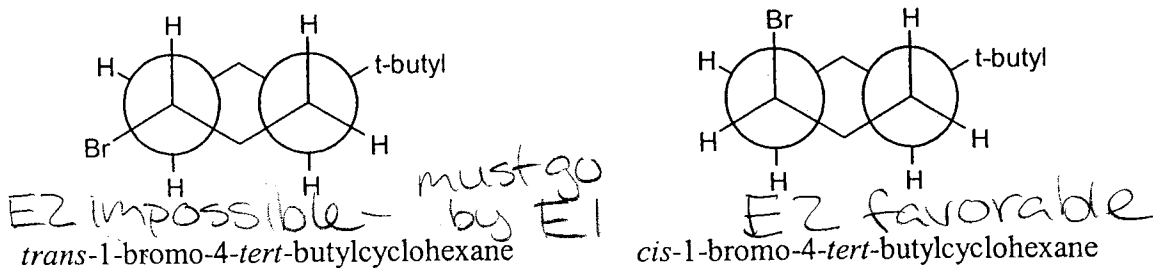
E2 requires anti-coplanar geometry of β -H & LG.

Part B: Stereochemistry of E2 Reactions

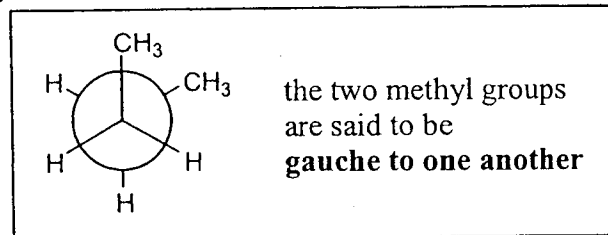
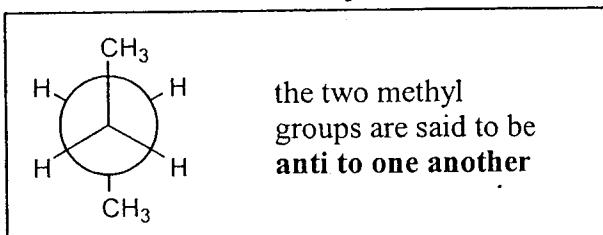
(What conformation favors one-step elimination (E2)?)

Model 5: Newman Projections of Molecules from Model 4

(note that the *t*-butyl group takes an equatorial position in each case)



Review of Newman Projection Terminology



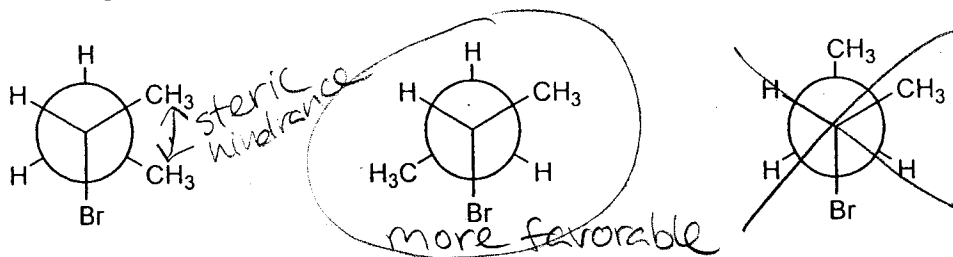
Critical Thinking Questions

13. Based on the information on the previous page, write the words "E2 favorable" under one structure in Model 5 and "E2 impossible-must go by E1" under the other.

see above

14. Circle the statement that is consistent with your conclusions above.
- For an E2 reaction to occur there must be an H **gauche** to the leaving group. **F**
 - For an E2 reaction to occur there must be an H **anti** to the leaving group. **T**

15. The three possible staggered conformations of (*S*)-2-bromobutane are shown below.

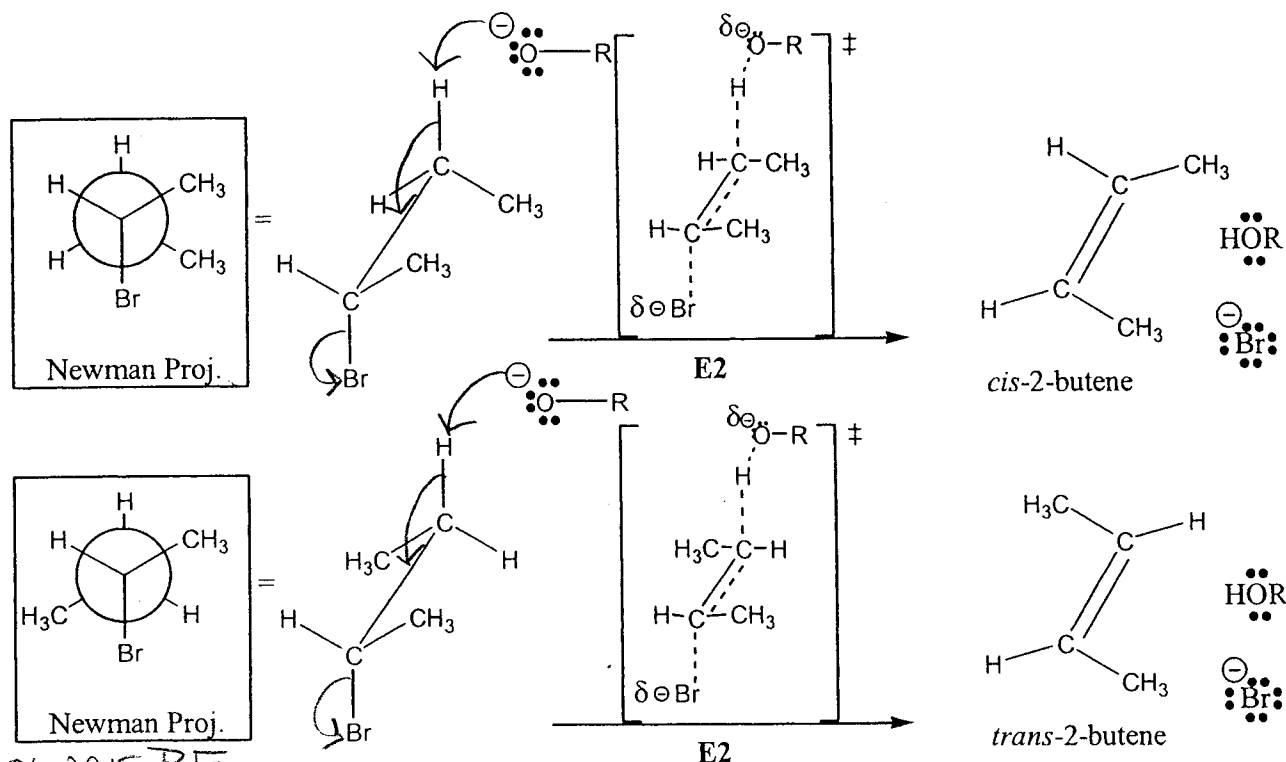


- a) Based on your conclusions above, cross out the conformation that cannot lead to an E2 reaction.

- b) Which of the remaining two conformations is more favorable, in terms of potential energy? Explain your reasoning.

Less steric hindrance between the methyl groups

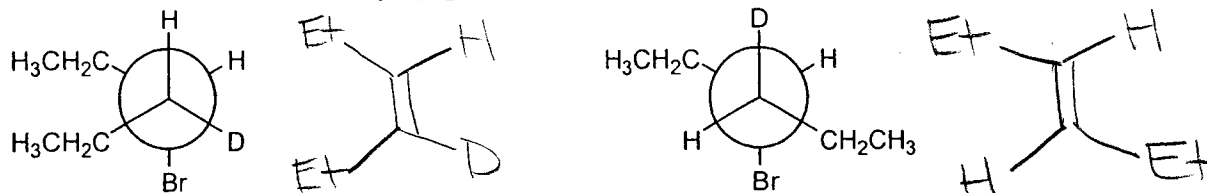
16. Below are Newman and "sawhorse" representations of the two conformations of (S)-2-bromobutane that can lead to E2 reactions, along with the products of these E2 reactions.



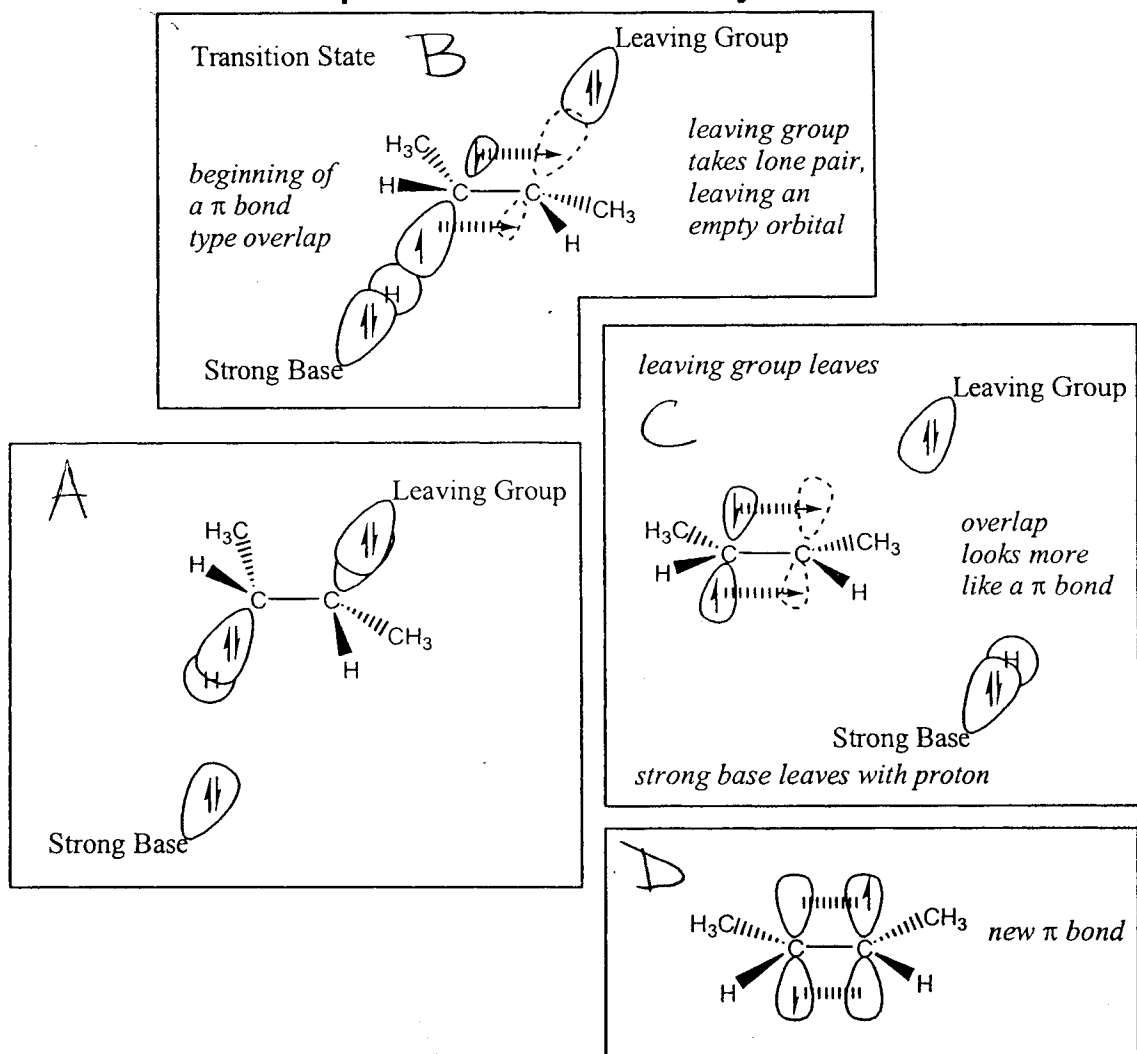
will spend more time in this conform.

- a) On the sawhorse representations of the reactants above, use curved arrows to show the flow of electrons during each E2 reaction. *see above*
- b) Are your curved arrows consistent with the electron changes depicted in the transition state for each reaction (shown in brackets above each reaction arrow)? *yes*
- c) Relate the following statement to the example above: "The reactions above are E2 reactions so the changes happen all at once in one step. This 'traps' the methyl groups: either **on the same side** of the newly forming double bond (*see* transition state leading to *cis* product), or **on opposite sides** of the newly forming double bond (*see* transition state leading to *trans* product)."
- d) Label one of the Newman Projections above with the words "**lower P.E. – will spend more time in this conformation.**"
- e) Based on the fact that each conformation gives exclusively the product shown, predict which will be more prevalent in the product mixture. *trans*-2-butene or *cis*-2-butene [circle one] and explain your reasoning. *lower E transition state has lower Ea & faster rxn rate & more prod.*
- f) Is your answer above consistent with the product distribution in Model 3? *yes*

17. For each conformation of the deuterated 3-bromoheptane stereoisomer below, draw the alkene product that will form if the conformation shown undergoes an E2 reaction. (**Deuterated** means that one or more of the H atoms has been replaced with a "heavy" hydrogen called a deuterium atom (D). Assume D and H have the same chemical reactivity. (e.g. D₂O has the same chemistry as H₂O))



Model 6: Orbital Explanation for "Anti-Only" E2 Reaction



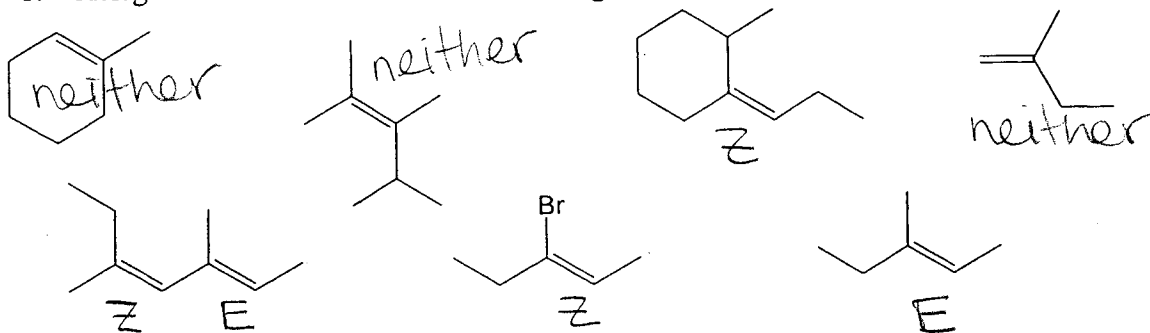
Critical Thinking Questions

18. Label the boxes above A-D according to the order in which they occur in an E2 rxn.

see above

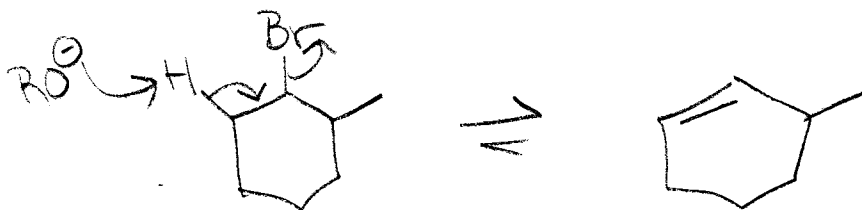
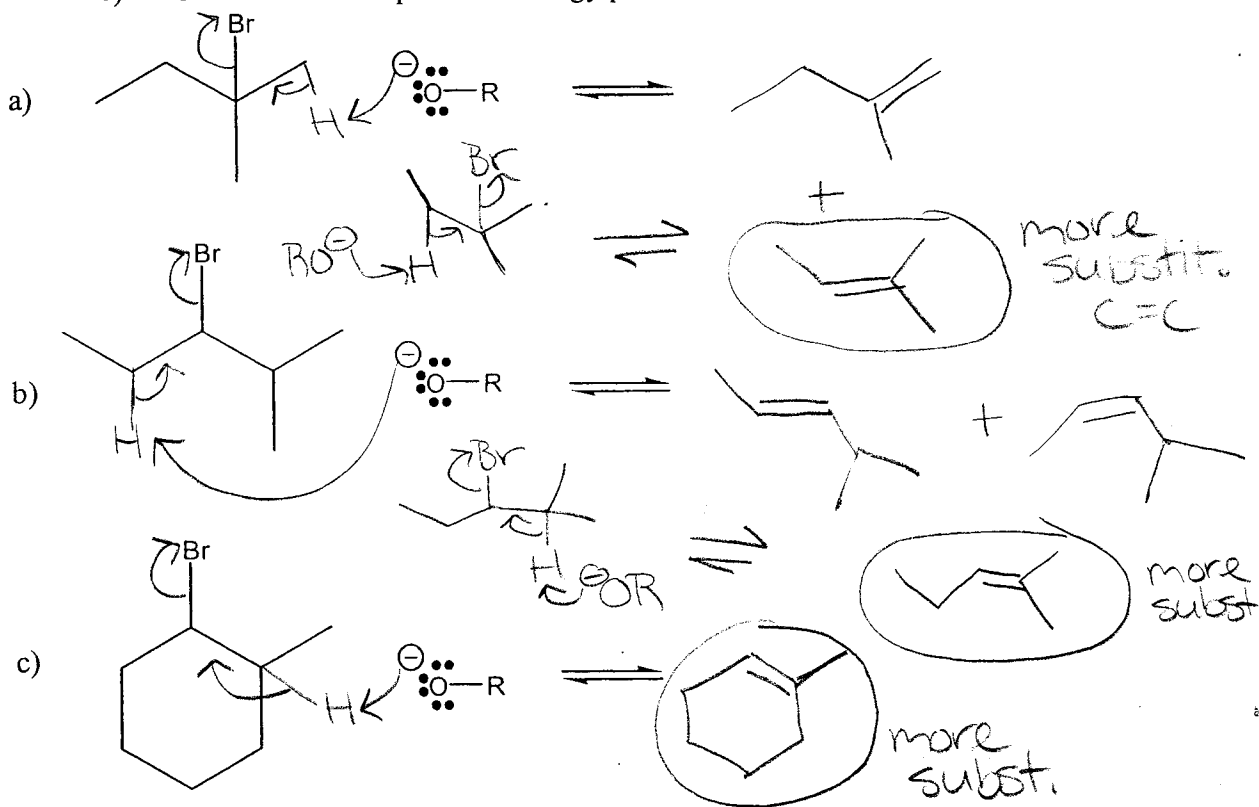
Exercises for Part A

1. Assign each double bond in the following molecules as E, Z, or *neither*.



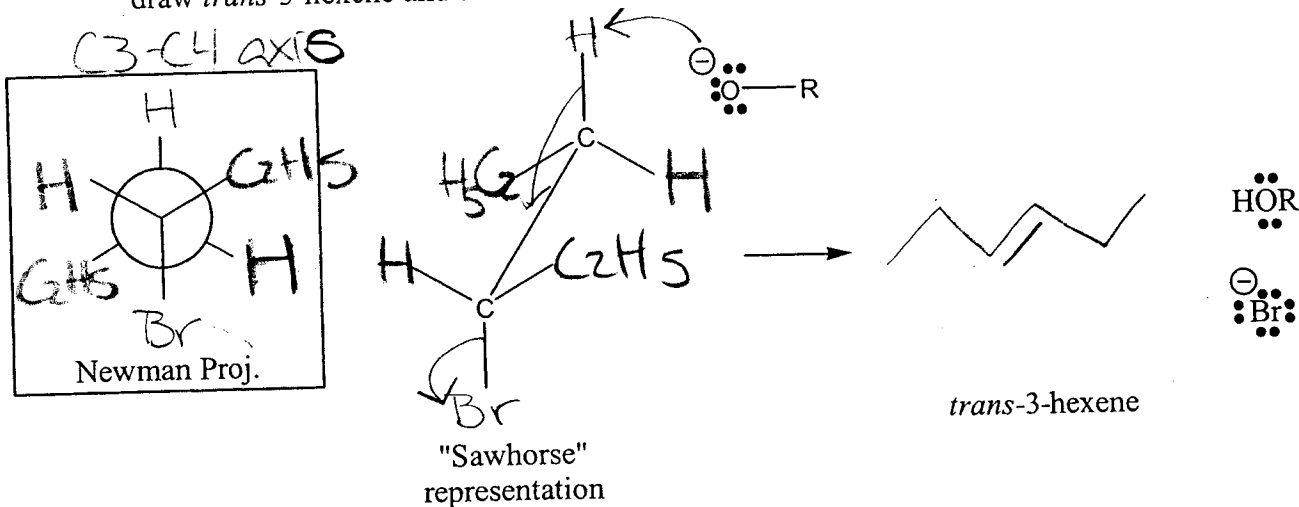
2. For each of the following pairs of reactants

- Draw all possible E2 products.
- Use curved arrows to show the formation of each different product. Redraw the reactants for each new product so as to clearly show each set of arrows.
- Circle the lowest potential energy product in each case.

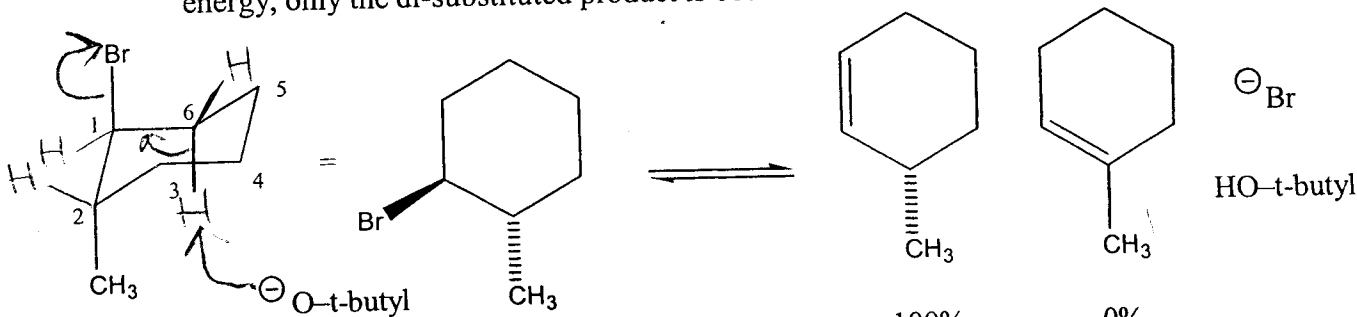


Exercises for Part B

4. Complete the following Newman and sawhorse representations of (S)-3-bromohexane showing a conformation that would give rise to *trans*-3-hexene. Also draw *trans*-3-hexene and show the mechanism of formation using curved arrows.



5. Even though the tri-substituted alkene product on the right is lower in potential energy, only the di-substituted product is observed.



- a) Draw in the β -H's and show the mechanism on the reaction above.
b) Explain why the tri-substituted product does NOT form.

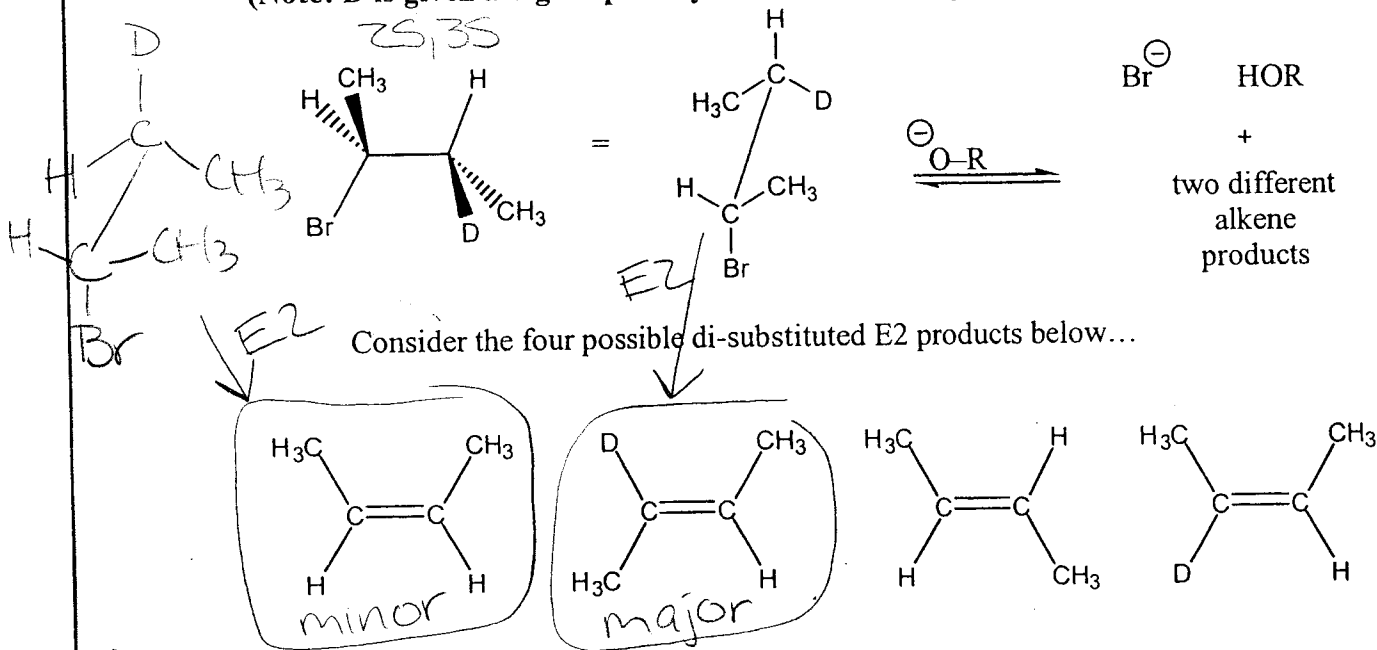
The tri-substituted product does NOT form b/c the β -H can NOT be anti-coplanar to the bromine atom.

6. Mark TRUE each of the following statements that helps explain the product distribution in Model 3. (More than one may be true.)

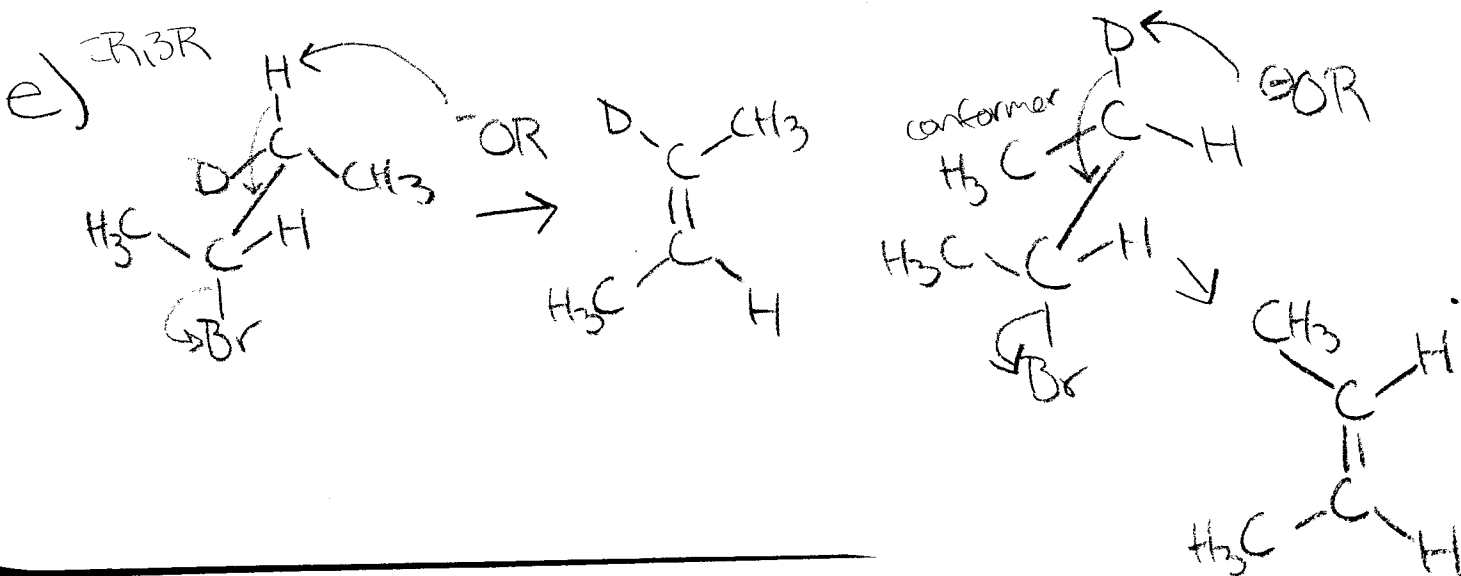
- True I. The conformation leading to the *cis* product is less favorable than the conformation leading to the *trans* product.
- True II. The methyl groups of the *trans* product are farther apart than in the *cis* product. This leads to less steric hindrance and therefore lower P.E. for the *trans* product.
- True III. A terminal double bond (one at the end of a chain) is higher in potential energy than an internal double bond (one in the middle of a chain).

7. Deuterium (D) has nearly identical reactivity as hydrogen (H). Consequently, the one-step elimination of Br from (S,S)-2-bromo-3-deuterobutane (shown below) yields two different alkene products.

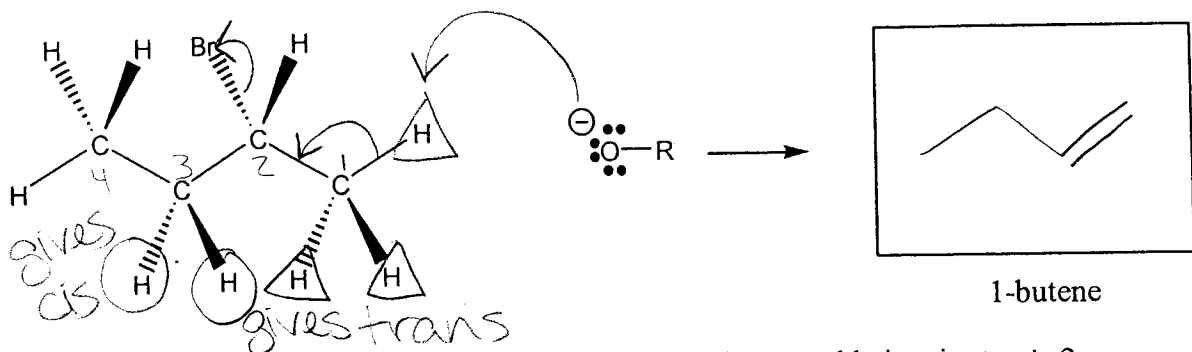
(Note: D is given a higher priority than H when assigning absolute configuration.)



- d) *R,R*-2-bromo-3-deutero-butane
- Circle the two that could be produced by E2 reaction of the (S,S) stereoisomer. *see above*
 - Mark one as the "major product" and one as the "minor product." *see above*
 - Draw a sawhorse representation of the conformation that would give rise to each of these two products. *see above*
 - Draw and name the enantiomer of (S,S)-2-bromo-3-deuterobutane. *look left*
 - Could E2 reaction with this stereoisomer give rise to either of the two uncircled alkene products? Show the sawhorse representation of the conformation giving rise to each product. *NO - see below*
 - Draw AND NAME a diastereomer of 2-bromo-3-deuterobutane: either (S,R) or (R,S)-2-bromo-3-deuterobutane. *see next page*
 - Can this stereoisomer give rise to the other two products? If so, show the sawhorse representation of the conformation giving rise to each product.



8. On the following drawing of (R)-2-bromobutane...



- Circle any H that, if removed in an E2 reaction, would give rise to *cis*-2-butene, and label it "gives *cis*."
- Circle any H that, if removed in an E2 reaction, would give rise to *trans*-2-butene, and label it "gives *trans*."
- Draw 1-butene in the box provided.
- Put a triangle around any H that, if removed, would give rise to 1-butene.
- Use curved arrows to show the mechanism of an E2 reaction leading to 1-butene.
- A student predicts that the ratio of *trans*-2-butene to 1-butene should be 1:3 in the final product mixture. Explain how she came up with the ratio 1:3, and explain the **flaw** in her reasoning.

The student only looked at the probability based on the number of β-H's available. The flaw was to ignore the relative energies of the con conformers.

7. f) Yes, the *ZR, 3S* or *ZS, 3R* stereoisomers give rise to the other 2 products from previous page (2-bromo-3-deutero butane)

