

Exam Booklet No.

**CHEM 2410 – Organic Chemistry 1 – Fall 2017**

Instructors: Erin Witteck &amp; Paul Bracher

**Hour Examination #2**Wednesday, October 18<sup>th</sup>, 2017

6:10–8:10 p.m. in the Lecture Halls at Saint Louis University

Student Name (Printed)	<b>Solutions</b>
Student Signature	<b>N/A</b>

**Instructions & Scoring**

- Please write your answers on the official answer sheet. No answers marked in this booklet will be graded.
- You may use a plastic model kit. No electronic resources or note sheets are permitted, and you may not communicate with others.
- Your exam answer sheet may be copied or scanned.
- The examination room may be monitored by audio, photo, and/or video recording.

Problem	Points Earned	Points Available
I		60
II		12
III		16
IV		6
V		6
TOTAL		100

## Examination Instructions

**DO NOT TURN THE PAGE ON THIS BOOKLET UNTIL DIRECTED BY A PROCTOR TO BEGIN**

**Please Make Sure to Do the Following Before Starting Your Exam**

1. Both print your name and sign the front of the answer sheet and this exam booklet in the appropriate boxes.
2. Also print your name at the top of the back of the answer sheet.
3. Enter your SLU Banner ID number on the front of the answer sheet and bubble the corresponding numbers. Failure to do this correctly will result in the loss of 2 points. If you have forgotten your Banner ID, tell a proctor.
4. Write the serial number of this exam booklet on your answer sheet in the appropriate box.
5. Check the “Hold for Pick-Up” box on the back of the answer sheet if you want your graded sheet withheld from the distribution pile on Monday and handed back to you privately. Checking this box will delay your receipt of your graded exam.

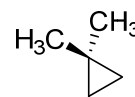
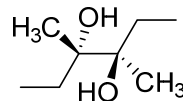
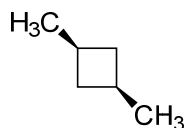
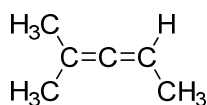
**Please Make Sure to Do the Following After Completing Your Exam**

1. Ensure that all of your selected circles are darkened completely.
2. Submit your answer sheet, exam booklet, data tables, and scratch paper to the proctors. You may not remove these items from the exam room.

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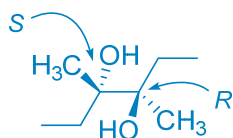
**Problem I.** Multiple Choice (60 points total). Correct answers score +3 points, answers of 'E' score +1 point, and incorrect answers score 0 points. Questions filled with zero or multiple responses will score 0 points. For each question, select the best and most complete answer of the choices given. Bubble the answer, darkly, in the space provided on the answer sheet. For all questions that ask you to name or count compounds or products, include all distinct compounds that not interconvertible under ambient conditions (i.e., include or count different constitutional isomers and stereoisomers separately, but not different conformations that can interconvert).

(1)     C     How many of the following compounds is/are achiral and not meso?

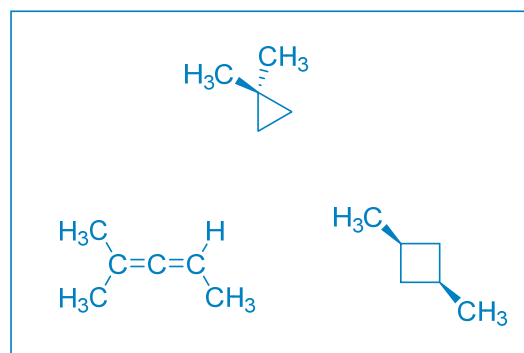


- (A) one
- (B) two
- (C) three
- (D) four

A compound is achiral if it is superposable with its mirror image. Compounds are meso if they are achiral and have at least two stereogenic carbon atoms.



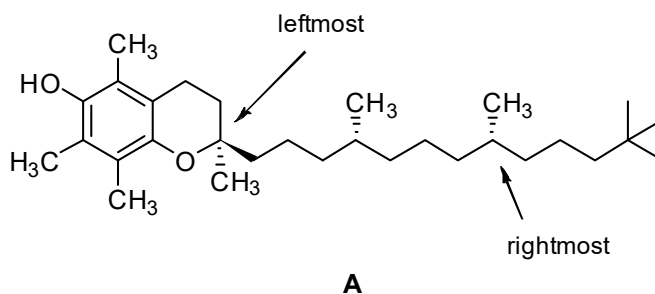
achiral  
meso  
(has stereogenic centers but is achiral)



achiral  
not meso  
(do not have any stereocenters)

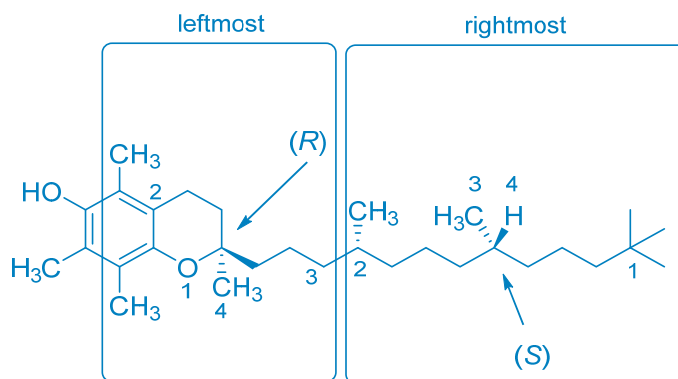
Where you've seen it: Similar to Fall 2017 Quiz #2 Question 3. Allene was covered in Fall 2017 Quiz #2, others have been covered in some form in the suggested problems from the textbook. Three successive clicker questions in Fall 2017 Lecture 19 covered the identification of a compound as chiral/achiral and meso/not meso. Also similar to Fall 2016 Exam #2 Problem I-9.

- (2)     B     What are the absolute configurations of the two labeled stereogenic centers in compound **A**?



- (A) leftmost: *R*; rightmost: *R*  
(B) leftmost: *R*; rightmost: *S*  
(C) leftmost: *S*; rightmost: *R*  
(D) leftmost: *S*; rightmost: *S*

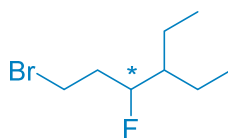
The assignments for each stereocenter (individually boxed) are shown below. The Cahn–Ingold–Prelog priorities are ranked for each of the four groups around each stereocenter.



Where you've seen it: Format almost identical to Fall 2017 Quiz #2 Question 6.

- (3)     B     How many stereogenic centers are found in 1-bromo-4-ethyl-3-fluorohexane?
- (A) no stereogenic centers  
(B) one stereogenic center  
(C) two stereogenic centers  
(D) three stereogenic centers

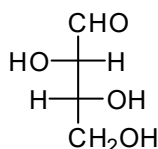
Let's begin by drawing a structure of the compound in question, 1-bromo-4-ethyl-3-fluorohexane:



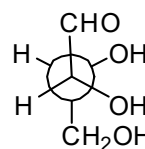
Note that the only stereogenic carbon atom—a carbon atom bonded to four different groups—is the third carbon atom, marked with an asterisk (\*). C1 is not a stereocenter because it has two hydrogen atoms, C4 is not a stereocenter because that carbon is bonded to two ethyl groups.

Where you've seen it: Similar to Fall 2017 Quiz #2 Question 1.

- (4)       **B**       If compound **B** has a specific rotation of  $+24 \text{ deg} \cdot \text{g}^{-1} \cdot \text{mL} \cdot \text{dm}^{-1}$  at a particular temperature and wavelength of light, what is the specific rotation of compound **C** at the exact same temperature and wavelength?



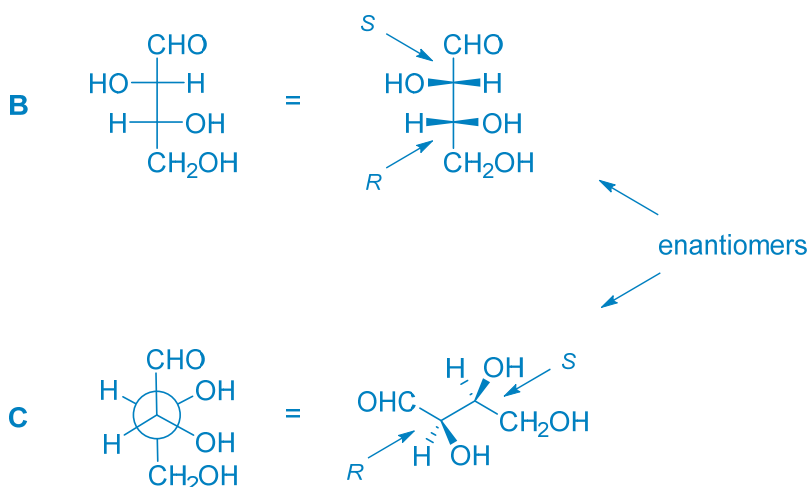
**B**



**C**

- (A)  $+24 \text{ deg} \cdot \text{g}^{-1} \cdot \text{mL} \cdot \text{dm}^{-1}$   
(B)  $-24 \text{ deg} \cdot \text{g}^{-1} \cdot \text{mL} \cdot \text{dm}^{-1}$   
(C)  $0 \text{ deg} \cdot \text{g}^{-1} \cdot \text{mL} \cdot \text{dm}^{-1}$   
(D) there is not enough information provided to determine the specific rotation of **C**

Compounds **B** and **C** have the same connectivity of atoms, so they are either stereoisomers or identical. We must determine the absolute stereochemistry of their two stereocenters in order to determine their relationship:



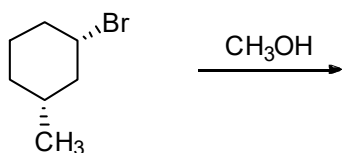
The compounds are enantiomers—nonsuperposable mirror images—as the C2 and C3 designations are both flipped between **B** and **C**. Enantiomers have specific rotations that are of equal magnitude but opposite sign.

Where you've seen it: Format identical to Fall 2017 Quiz #2 Question 20. Similar to Fall 2017 Quiz #2 Questions 8 and 10.

- (5)     A     Which of the following is best estimated by measuring the concentrations of the reactants and products of a reaction at equilibrium?
- (A)  $\Delta G^\circ$   
 (B)  $\Delta H^\circ$   
 (C)  $\Delta S^\circ$   
 (D)  $[\alpha]$

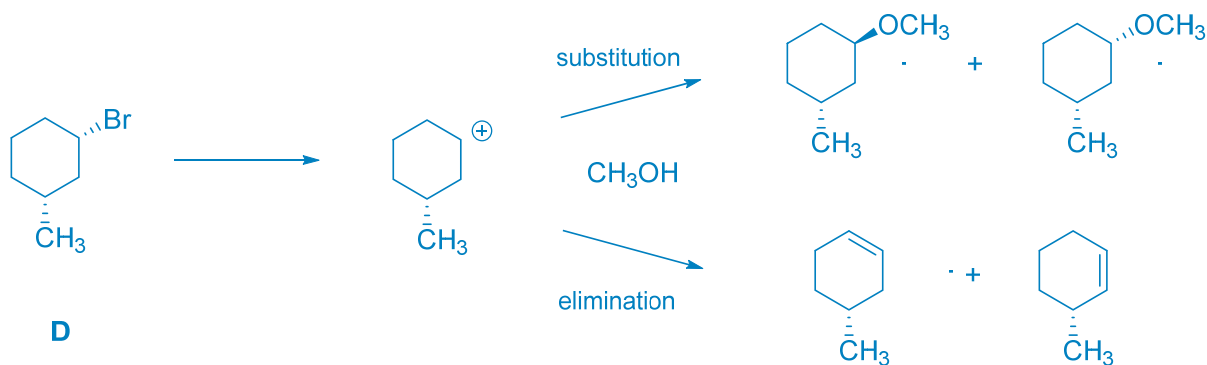
Measuring the concentrations of the components of a system at equilibrium is one way to determine the equilibrium constant,  $K$ . From  $K$ , we can calculate  $\Delta G^\circ$  by  $\Delta G^\circ = -RT \ln K$ . We can measure  $\Delta H^\circ$  by measuring the heat liberated or absorbed by a reaction. We cannot measure  $\Delta S^\circ$  directly, but we can determine it following measurement of  $\Delta G^\circ$  and  $\Delta H^\circ$ .  $[\alpha]$ , specific rotation, is determined by observation of how a sample rotates plane-polarized light.

- (6)     D     How many different substitution and elimination products are possible when compound **D** is heated in methanol? Assume that any carbocation intermediates do not undergo rearrangement.



- (A) one product  
(B) two products  
(C) three products  
(D) four products

Compound **D** is a secondary alkyl halide and methanol is both a weak nucleophile and a weak base. These conditions favor a competition between  $S_N1$  and  $E1$  reactions. There are two substitution products, as the methanol can attack either face of the carbocation intermediate, and two elimination products, as the carbocation has  $\beta$ -hydrogens on two inequivalent adjacent carbon atoms. Were **D** also to react with second-order kinetics, there would be no additional products from those already identified.



Where you've seen it: Similar ideas to Summer 2016 Quiz #2 Problem I-9

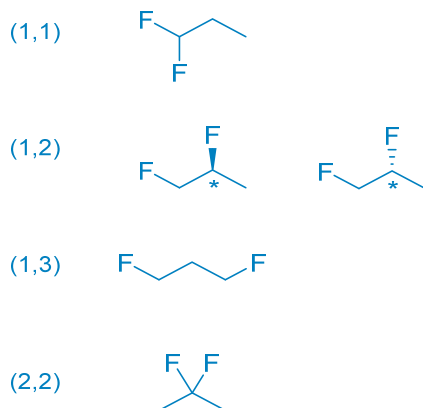
(7)     C     How many different compounds of formula  $C_3H_6F_2$  exist that are optically active?

- (A) zero
- (B) one
- (C) two
- (D) three or more

It is best to take a systematic approach to problems where you'll need to keep track of structural variation so that you avoid undercounting the possibilities or counting one or more possibilities twice. There is only one skeletal framework possible for three carbons with eight H/F atoms:



We can place the substituents along the chain at different positions. In cases where a stereogenic carbon is generated by virtue of having a carbon atom with four different substituents, both *R* and *S* designations should be drawn. Be careful in noting that 1,1-substitution is the same as 3,3-substitution and 1,2- is the same as 2,3-. Don't count identical patterns twice!

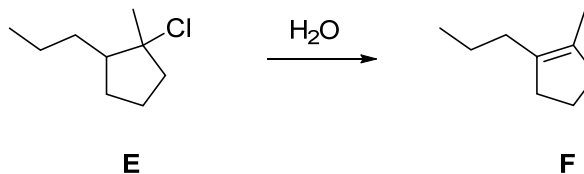


The two optically active isomers are marked with an asterisk.

Where you've seen it: Format identical to Fall 2017 Quiz #2 Questions 4 and 5.



- (8)       D       Which of the following will not have a significant effect on the rate of the following reaction?

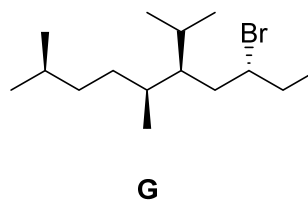


- (A) changing chlorine to iodine in **E**  
(B) changing the solvent from water to hexane  
(C) heating the reaction  
(D) none of the above – all three changes would affect the rate

This reaction appears to be an elimination of HCl with an E1 mechanism (the substrate is a tertiary alkyl halide and water is a weak base). Making the halide a better leaving group, changing the polarity of the solvent (such that the stabilization of the intermediate carbocation is affected), and heating the reaction will all have significant effects on the rate of the reaction.

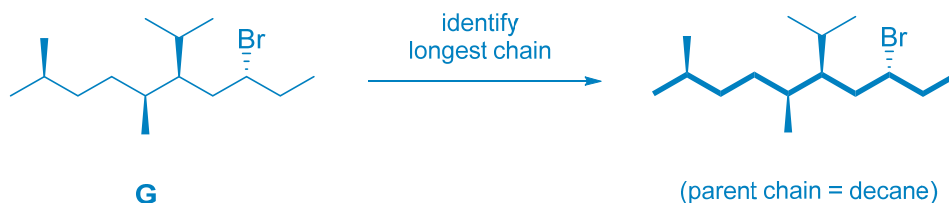
Where you've seen it: Similar to Fall 2016 Exam #2 Problem I-23. In-class clicker question about rate, discussion section question about rate, Problem 8.15 in the Smith, 4<sup>th</sup> edition text.

- (9)       A       What is the IUPAC systematic name for compound **G**?

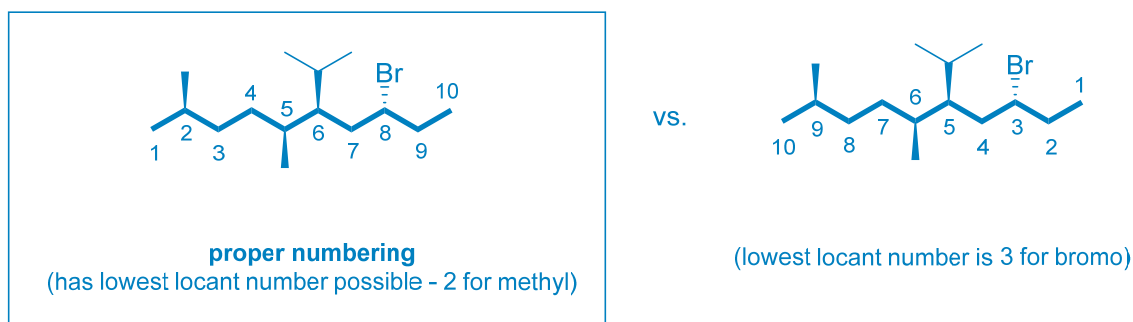


- (A) (5*S*,6*R*,8*R*)-8-bromo-6-isopropyl-2,5-dimethyldecane  
(B) (2*S*,5*S*,6*S*,8*R*)-8-bromo-2,5-dimethyl-6-isopropyldecane  
(C) (5*S*,6*S*,8*R*)-8-bromo-6-isopropyl-2,5-dimethyldecane  
(D) (3*S*,5*R*,6*S*)-3-bromo-5-isopropyl-6,9-dimethyldecane

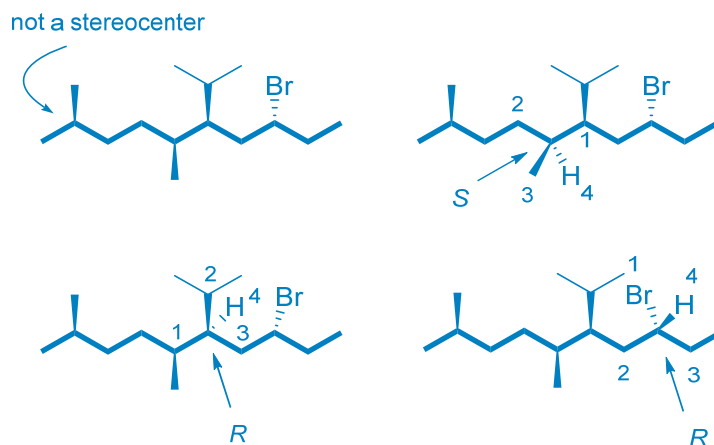
You know the drill: In naming alkyl halides, we begin by identifying the longest chain of carbon atoms. Here, that chain (of ten carbons) is marked in bold:



Next, we have to number the chain starting from the end closest to a substituent:



Next, we identify the stereocenters and assign *R/S* designations to them. Be careful with your assignments of Cahn–Ingold–Prelog priorities to the groups around each stereogenic carbon atom:

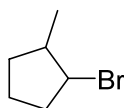


Finally, alphabetize the substituents, insert the locants, insert the stereochemical prefixes, and you're done!



Where you've seen it: Similar to Fall 2016 Exam #2 Problem I-3, Summer 2016 Exam #2 Problem III, Summer 2016 Quiz #2 Problem I-1.

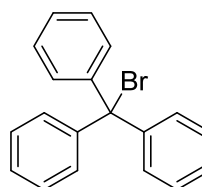
- (10)     B     Which of the following alkyl halides is most likely to form an elimination product through first-order kinetics?



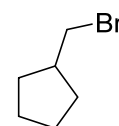
(A)



(B)

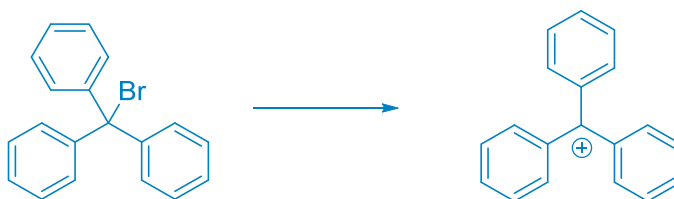


(C)



(D)

In order to form an elimination product through first-order kinetics, we need (i) to be able to generate a stable carbocation and (ii) to have  $\beta$ -hydrogens capable of elimination. For compound (C), bromide is easily lost to form a carbocation that is stabilized by extensive delocalization by a resonance effect, but there are no hydrogens capable of elimination:

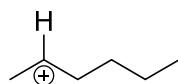
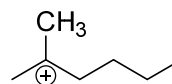


very stable carbocation, but it has no  $\beta$ -hydrogens capable of being eliminated

Compounds (A), (B), and (D) all have  $\beta$ -hydrogens capable of being eliminated. Of these three choices, compound (B) most readily loses bromide to generate a carbocation because it is the most substituted carbocation (tertiary vs. secondary vs. primary). The added alkyl groups stabilize the carbocation by hyperconjugation, making the E1 reaction proceed faster.

Where you've seen it: Similar ideas to Summer 2016 Quiz #2 Problem I-9

(11)     C     Which of the following statements best describes carbocations **H** and **J**?

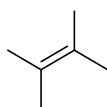
**H****J**

- (A) **H** is more stable due to the interaction of the 1s orbital on H with the empty *p* orbital on C
- (B) **H** is more stable due the interaction of the 1s orbital on H with the empty  $\sigma^*$  orbital on C
- (C) **J** is more stable due to the interaction of C–H  $\sigma$  bonding orbitals with the empty *p* orbital on C
- (D) **J** is more stable due to the interaction of C–H  $\sigma$  bonding orbitals with the empty  $\sigma^*$  orbital on C

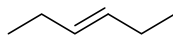
As noted in the two structures, the carbocations differ in that the replacement of a hydrogen atom in **H** with a methyl group in **J** makes **H** a secondary carbocation and **J** a tertiary carbocation. Increasing alkyl group substitution helps stabilize carbocations by hyperconjugation. Hyperconjugation involves the donation of electron density from  $\sigma$  bonds (filled  $\sigma$  molecular orbitals) into the adjacent vacant *2p* orbital on the carbon bearing the positive formal charge.

Where you've seen it: Identical format to Fall 2016 Exam #2 Problem I-14. Similar ideas to Fall 2015 Exam #2 Problem I-1.

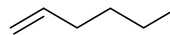
(12)     A     Which of the following compounds has the most stable C=C  $\pi$  bond?



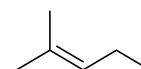
(A)



(B)



(C)



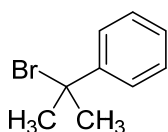
(D)

Alkenes are stabilized by increasing substitution by alkyl groups. The underlying reason for this observation is that the alkyl groups enable stabilizing hyperconjugation interactions of filled C–H and C–C  $\sigma$  bonds donating

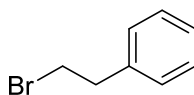
electron density into the empty  $C=C \pi^*$  orbital of the alkene. Here, alkene (A) is the most substituted (tetrasubstituted) and is thus the most stable. Alkene (C) is the least substituted (monosubstituted) and is the least stable of the alkenes shown.

Where you've seen it: Clicker question in Fall 2017 Lecture 18. Similar to Fall 2016 Exam #2 Problem I-18, Summer 2016 Exam #2 Problem I-6.

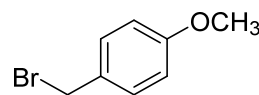
- (13)     B     For which of the following compounds would heterolytic cleavage of the carbon–bromine bond be the least facile (*i.e.*, be the most endothermic)?



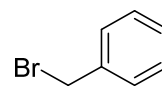
(A)



(B)



(C)



(D)

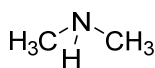
Bond cleavage is always endothermic, so the transition state will resemble the product. For heterolytic cleavage of a C–Br bond, the product is bromide and a carbocation. So, the speed of the cleavage will depend on the stability of the resulting carbocation—whichever gives the most stable carbocation will be produced the fastest. Here, the carbocations formed from (A), (C), and (D) all have several resonance forms, while that for (B) has the positive charge localized on a primary carbon (a very high energy carbocation). So, the carbocation for (B) will form the slowest.

Where you've seen it: Identical format to Fall 2016 Exam #2 Problem I-15.

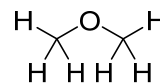
- (14)     B     Which of the following is a protic compound that would generally be considered an unwise choice of solvent for running many  $S_N2$  reactions?



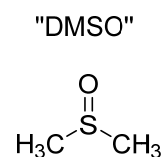
(A)



(B)



(C)



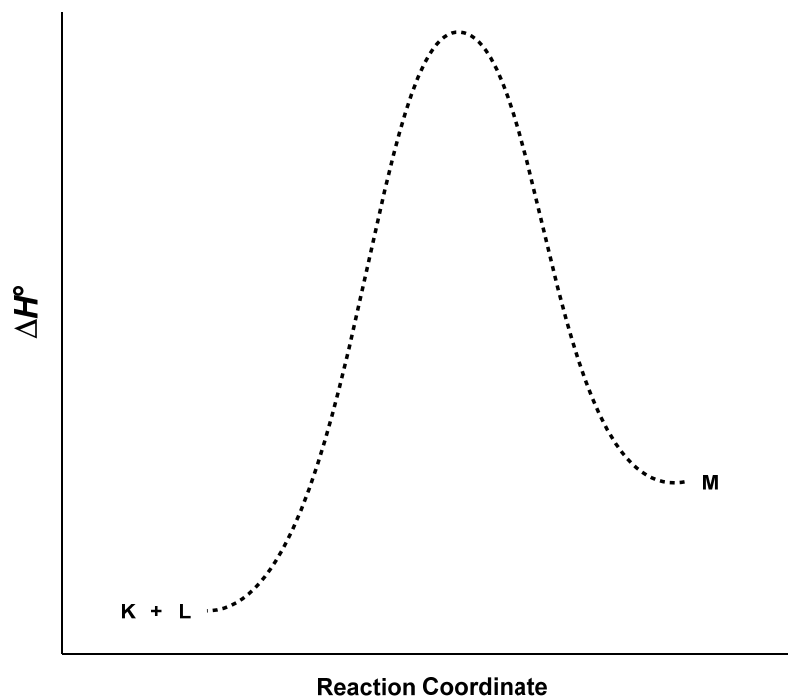
(D)

A protic compound is one capable of donating hydrogen bonds because one or more hydrogen atoms is bonded to an electronegative element like F, O, or N. In the above compounds, all of the hydrogen atoms are bonded to carbon atoms except for the single H atom bonded to nitrogen in compound (B), dimethylamine.

Note that choice (D), DMSO, is a very common polar, aprotic solvent.

Where you've seen it: Similar to Fall 2016 Exam #2 Problem I-5.

- (15)     D     Which of the following statements is not true of a reaction that corresponds to the following energy diagram?

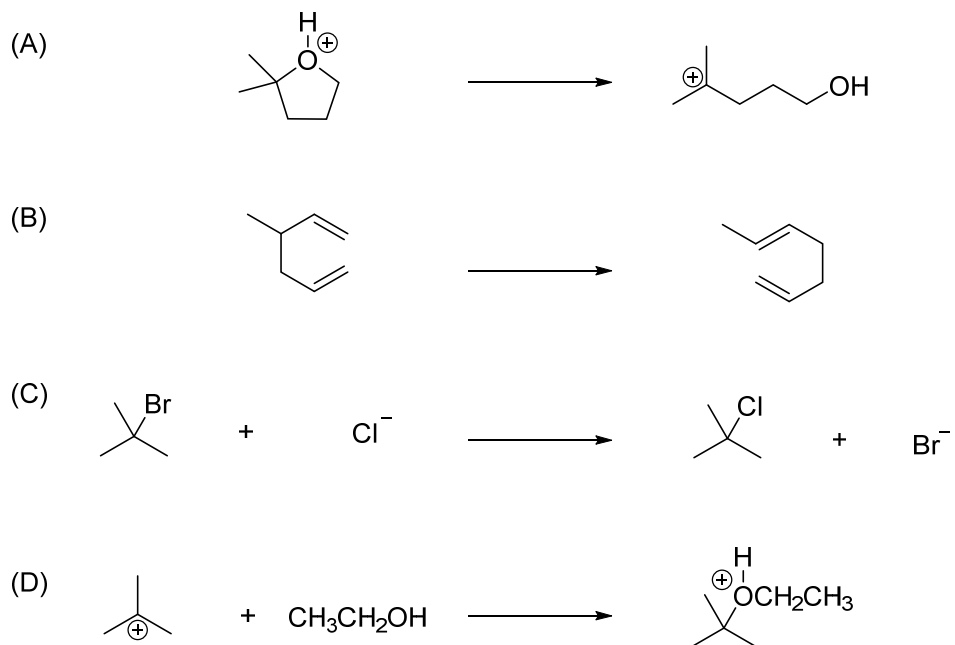


- (A) the reaction is endothermic
- (B) the equilibrium will favor the reactants (K & L)
- (C) the reaction is concerted
- (D) the reaction has one intermediate

Statement (A) is correct—the reaction is endothermic as the product lies higher-in-energy than the starting materials. Statement (B) is correct—the equilibrium will favor the starting materials because they are lower-in-energy than the product. Statement (C) is correct—the reaction is concerted because it takes place in a single step with a single transition state and no intermediate states. Statement (D) is incorrect—the reaction has no intermediates. Any intermediate would appear as a local minimum (trough) on the pathway from the starting materials to the product.

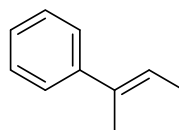
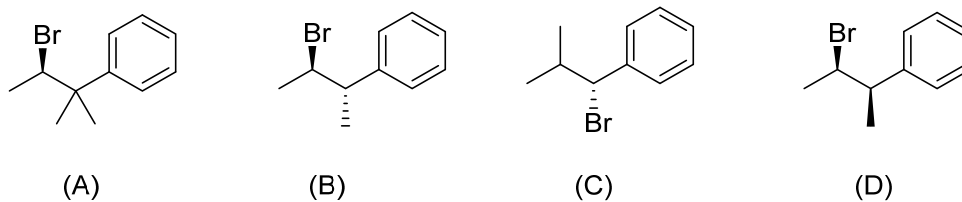
Where you've seen it: Similar to Summer 2016 Exam #2 Problem I-12, Summer 2016 Quiz #2 Problem I-10.

- (16)     A     Which of the following reactions would most likely result in the greatest increase in the entropy of the system (i.e., which reaction has the highest  $\Delta S^\circ$ )? Assume that solvation effects do not play a significant role.



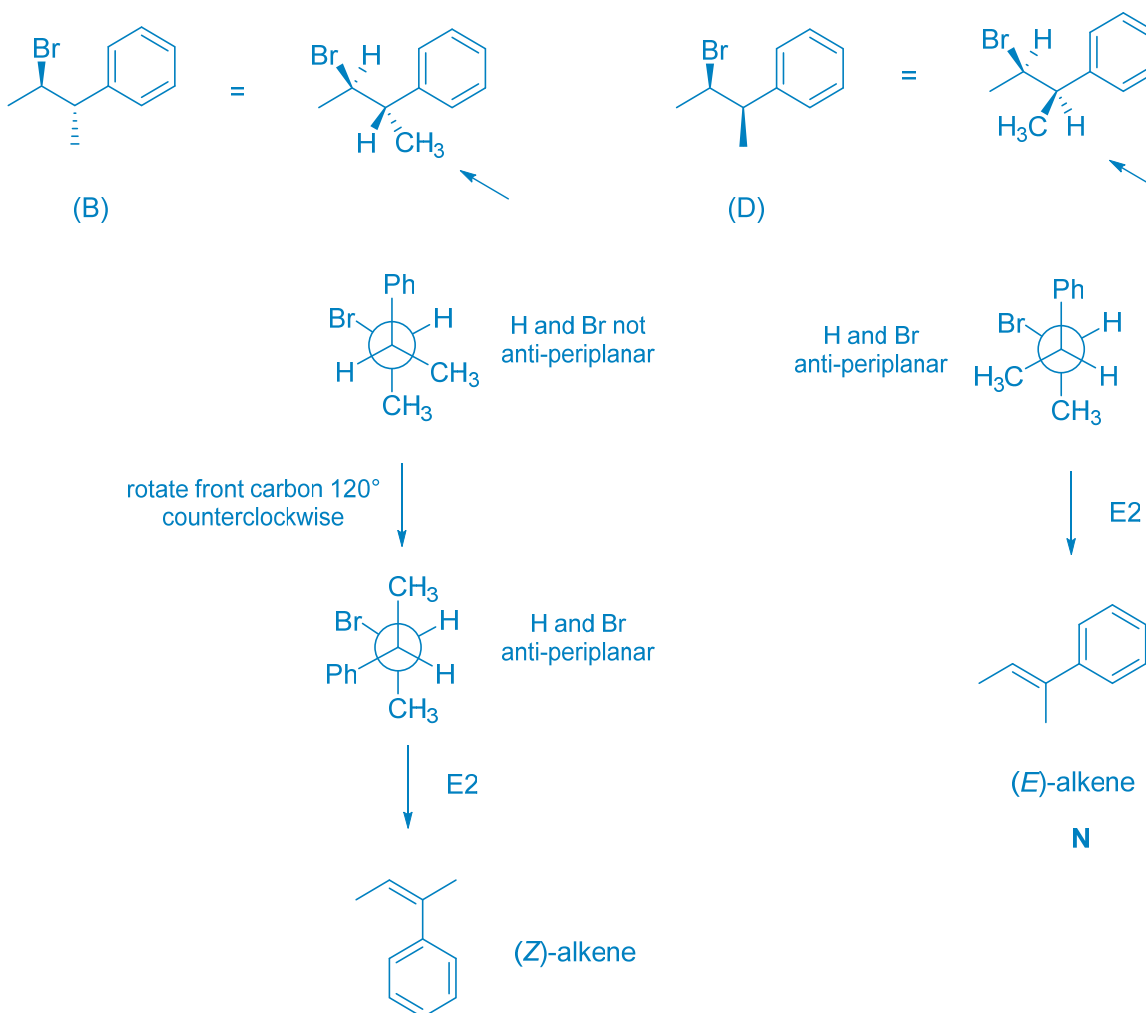
Reaction (A) should be associated with a positive  $\Delta S^\circ$  because a ring is opening up to form a linear structure. There's nothing in reactions (B) and (C) to suggest any large change in entropy. In reaction (D), two reactants combine to form one product, which should be associated with a negative  $\Delta S^\circ$  (unfavorable as far as entropy goes).

- (17)     D     What alkyl halide would produce **N** upon reaction with  $\text{NaOCH}_3$ ?

**N**

We have alkyl bromides reacting with a strong base to produce an alkene. We expect the dominant reaction to be E2 elimination. As such, we are looking to preferentially eliminate (i) the  $\beta$ -hydrogen that can be in a conformation that places it anti-periplanar to the halogen atom, (ii) that leads to the most substituted product, (iii) with a preference for placing the larger groups *trans* over *cis* if all else is equal.

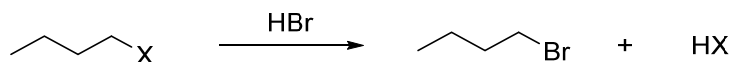
Right away, we can eliminate choices (A) and (C) because they have a different carbon backbone from the desired product. We need only compare choices (B) and (D), being sure to carefully translate their given stereochemistry to Newman projections. We are going to eliminate the proton on the tertiary carbon of each choice to give the more-substituted Zaitsev product. So, we need to find the conformation of each choice that has that H atom anti-periplanar to the bromine. After this analysis, we find that only choice (D) yields the correct diastereomer to match the desired product, **N**.



Where you've seen it: Similar to Fall 2016 Exam #2 Problem II-1, Summer 2016 Exam #2 Question 7, Summer 2016 Quiz #2 Problem I-6 (among many other practice problems).



(18)     D     For what identity of “X” will this reaction proceed the fastest?

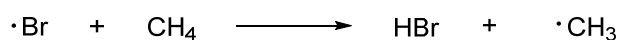


- (A) F
- (B) H
- (C)  $^+\text{NH}_3$
- (D)  $^+\text{OH}_2$

This reaction clearly proceeds via an  $\text{S}_{\text{N}}2$  mechanism as the bromide is substituting a leaving group on a primary carbon. The difference between the substrates is the identity of the leaving group, and we expect the reaction to proceed fastest for the best leaving group, which correlates with weakness of basicity. To compare the basicity of the four leaving groups ( $\text{F}^-$ ,  $\text{H}^-$ ,  $\text{NH}_3$ , and  $\text{H}_2\text{O}$ ) we need to compare the acidities of their conjugate acids ( $\text{HF}$ ,  $\text{H}_2$ ,  $\text{NH}_4^+$ ,  $\text{H}_3\text{O}^+$ ).  $\text{H}_3\text{O}^+$  is the strongest acid, so  $\text{H}_2\text{O}$  is the best leaving group and choice (D) will have the fastest reaction.

Where you’ve seen it: Pulled from Slide 5 in Fall 2017 Lecture 16.

(19)     C     Which of the following statements about this reaction is true?



- (A)  $\Delta H^\circ$  is negative, the transition state structure resembles the products
- (B)  $\Delta H^\circ$  is negative, the transition state structure resembles the reactants
- (C)  $\Delta H^\circ$  is positive, the transition state structure resembles the products
- (D)  $\Delta H^\circ$  is positive, the transition state structure resembles the reactants

Using the bond dissociation energy (BDE) table provided with the exam, we can calculate the  $\Delta H^\circ$  for this reaction by adding the energy of the broken  $\text{CH}_3\text{--H}$  bond (+410 kJ/mol) to the negative of the energy of the new/formed  $\text{H--Br}$  bond (366 kJ/mol). This gives:

$$\Delta H^\circ = +44 \text{ kJ/mol (endothermic)}$$

Since the step is endothermic, Hammond’s Postulate tells us the transition state will more closely the products than the reactants.

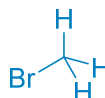
Where you’ve seen it: Calculation of Fall 2015 Exam #2 Problem II-1, then application of Hammond Postulate discussed extensively in Fall 2017 Lecture 17 slides.

(20)     A     Which of the following is the best explanation for why sodium cyanide reacts slower with 2-iodopropane than methyl bromide?

- (A) the electron cloud of the additional alkyl substituents hinders access to the vacant  $\sigma^*$  orbital of the C–X bond
- (B) iodide is a better leaving group than bromide, so the C–X  $\sigma$  bond is weaker and more easily substituted
- (C) weak bases favor first-order kinetics, so the identity of the nucleophile does not factor into the rate law
- (D) the donation of electron density from a filled  $\sigma$  bonding orbital to the vacant  $2p$  orbital stabilizes the formation of the carbocation by hyperconjugation



2-iodopropane



methyl bromide

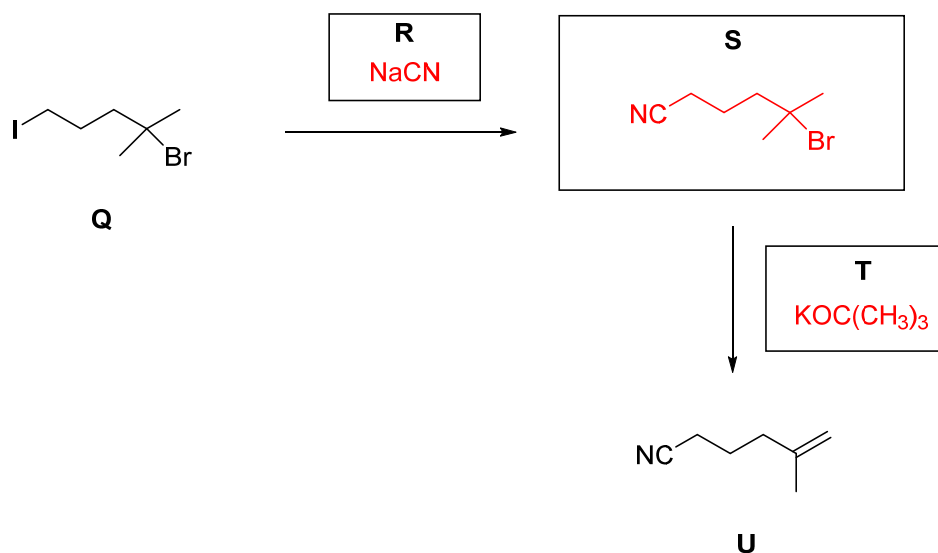
The key difference is that for 2-iodopropane the leaving group is on a secondary carbon and for methyl bromide the leaving group is just attached to a methyl group. Sodium cyanide is a good nucleophile and a weak base, so we expect both reactions to favor the  $S_N2$  mechanism since neither substrate is tertiary. The rate of  $S_N2$  reactions increases with decreasing substitution of the carbon with the leaving group because of reduced steric hindrance, as described in choice (A).

Choice (B) correctly notes that iodide is a better leaving group than bromide, but that doesn't explain the given data because the methyl bromide is reacting faster. Choice (C) describes what is observed for  $S_N1$  reactions, which is not applicable here. Choice (D) describes hyperconjugation, but that does not explain the data presented here because the reaction proceeds by a concerted  $S_N2$  mechanism that does not involve carbocation intermediates.

Where you've seen it: A multiple-choice version of a free-response question on Summer 2016 Exam #2 (Problem IV-2).

**Problem II. Synthesis (12 points).**

(1) (6 points) For the synthetic scheme below, fill in the intermediate (**S**) and reagents necessary (**R** and **T**) to produce the desired alkene (**U**) from compound **Q**. It is not necessary to include solvents.



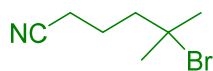
The starting material and product have the same number of carbons and same backbone structure. The task seems fairly straightforward—the iodine atom must be substituted with cyanide and  $\text{HBr}$  must be eliminated to form an alkene. The major decision to be made is which reaction should be performed first?

If we choose to run the substitution reaction first (using  $\text{CN}^-$  to displace  $\text{I}^-$ ), we can take advantage of the facts that iodide is a better leaving group than  $\text{Br}^-$  and that the iodide is primary (favorable for  $\text{S}_{\text{N}}2$ ) while the  $\text{Br}$  is tertiary (essentially unreactive for  $\text{S}_{\text{N}}2$ ). If we choose to run the elimination reaction first, we are not going to have as clean a reaction. While the structure of the  $\text{Br}$  (tertiary) favors a faster  $\text{E}2$  reaction than the structure of the  $\text{I}$  (primary), iodide is a better leaving group. So, if we run the elimination reaction first, we are going to risk a competition of the  $\text{Br}$  and  $\text{I}$  both being eliminated (and of the primary iodide being substituted for the alkoxide). Since we only want to eliminate the  $\text{Br}$ , it makes sense to take care of substituting the  $\text{I}$  atom first. For that, we need to use a source of cyanide ion ( $\text{CN}^-$ ) as the nucleophile.  $\text{NaCN}$  or  $\text{KCN}$  are good, standard choices for reagent **R**. The product of reacting one equivalent of cyanide with **Q** is **S** (shown above in red).

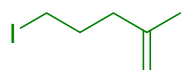
As suggested by the layout of the problem, intermediate **S** can be converted to the target **U** in one step. We must eliminate  $\text{HBr}$  from **S** to give an anti-Zaitsev (less-substituted alkene). We must use a bulky base to favor this regiochemistry. Standard choices for reagent **T** include potassium *tert*-butoxide ( $\text{tBuOK}$ ), DBU, and DBN. Note that since the  $\text{I}$  atom was substituted in the first step, we no longer have to worry about the previously mentioned competition.

Where you've seen it: Very similar to Fall 2015 Exam #2 Problem V.

Grading and partial credit:

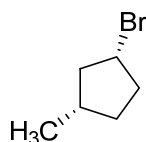
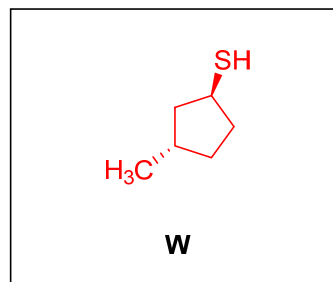
Identity of R:+2 for **R** = KCN, NaCN,  $\text{CN}^-$ +1 for **R** = HCN, CN,  $\text{NaCN}^-$ +1 for **R** =  $\text{KOC}(\text{CH}_3)_3$  or  $\text{NaOC}(\text{CH}_3)_3$ , or just  $^-\text{OC}(\text{CH}_3)_3$ 0 for **R** =  $\text{KOCH}_3$  or  $\text{NaOCH}_3$ , or just  $^-\text{OCH}_3$  or  $\text{NaNH}_2$  or  $\text{NaOH}$  or  $\text{NaOEt}$ Identity of S:+2 for **S** =

+1 for simple mistake on above (e.g., forgot bromine or missing/extra carbon)

+1 for **S** =Identity of T:+2 for **T** =  $\text{KOC}(\text{CH}_3)_3$  or  $\text{NaOC}(\text{CH}_3)_3$ , or just  $^-\text{OC}(\text{CH}_3)_3$ , DBU, DBN+1 for **T** = "bulky base"+1 for **T** =  $\text{NaOCH}(\text{CH}_3)_2$ +1 for **T** =  $\text{KOCH}_3$  or  $\text{NaOCH}_3$ , or just  $^-\text{OCH}_3$ ,  $\text{NaNH}_2$ ,  $\text{NaOH}$ ,  $\text{NaH}$ ,  $\text{H}^-$ ,  $\text{OH}^-$ ,  $\text{NaOEt}$ +1 for **T** =  $\text{NaCN}$ ,  $\text{CN}^-$ 0 for **T** = HCN, CN,  $\text{NaCN}^-$ , *t*-butyl, or alcohols

(2) (6 points, 3 points each) Write the major product of each reaction below in the corresponding box on your answer sheet.

(i)

**V****W**

Hydrosulfide anion is an excellent nucleophile and not an especially strong base, as  $pK_a(H_2S) = 7$ . DMSO is an excellent solvent to promote nucleophilicity of anions. These conditions favor  $S_N2$  substitution, which is possible on a  $2^\circ$  alkyl halide.

$S_N2$  reactions proceed with geometric inversion of configuration at the carbon atom that is attacked. That is why the SH group in the product has the opposite stereochemistry of the Br group in the starting material. The stereochemistry of the methyl group is unchanged in the product because no reaction occurs at that carbon atom.

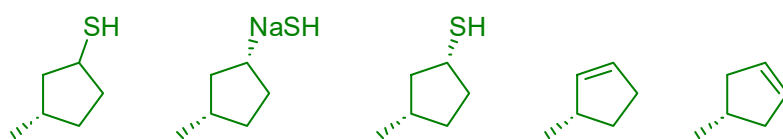
Where you've seen it: Very similar to Summer 2016 Exam #2 Problem I-1.

Grading and partial credit:

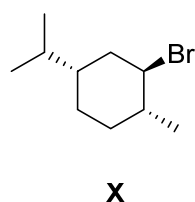
+3 for correct structure drawn in the box for **W**

+2 for its enantiomer

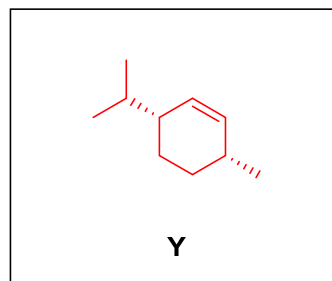
+1 for any of the following:



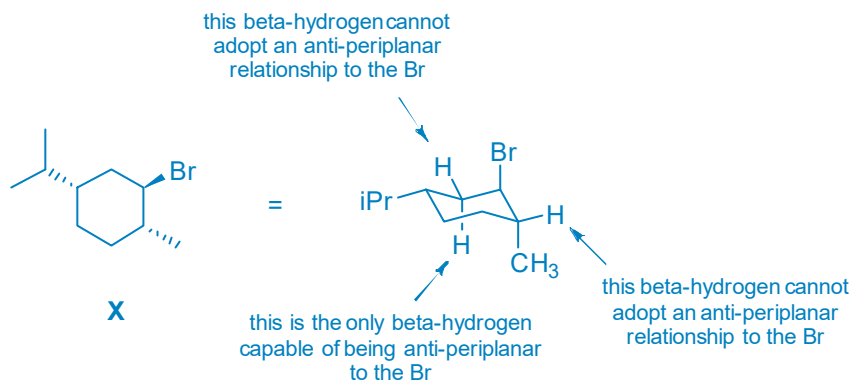
(ii)



NaOH



For a  $2^\circ$  alkyl halide and strong base like hydroxide, the  $E2$  reaction is favored. Of all the  $\beta$ -hydrogen atoms that can adopt an anti-periplanar configuration with the leaving group, we must decide which is the fastest to eliminate. In this case, there is only one hydrogen capable of being eliminated:



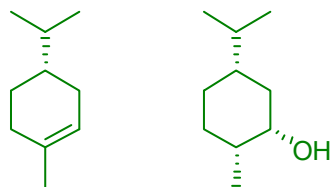
It might be tempting to eliminate the  $\beta$ -hydrogen that leads to a more-substituted alkene (tri- vs. di-) because you have Zaitsev's Rule in mind, but that hydrogen cannot adopt the necessary anti-periplanar relationship to be eliminated by an E2 mechanism.

Where you've seen it: Similar to Summer 2016 Exam #2 Problem I-7, Fall 2015 Exam #2 Problem I-5.

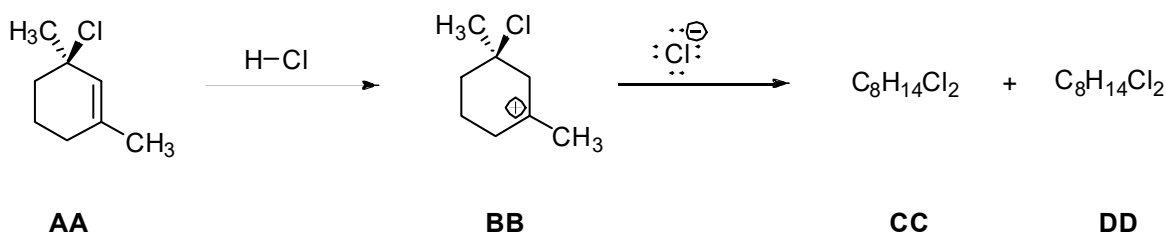
Grading and partial credit:

+3 for correct structure drawn in the box for **Y**

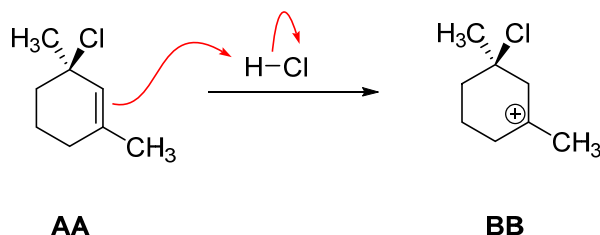
+1 for any of the following:



**Problem III.** Reaction Energy Diagram (16 points). Consider the reaction of **AA** with HCl to produce **CC** and **DD**.



(1) Draw the curved arrow mechanism for the production of **BB** from **AA**.



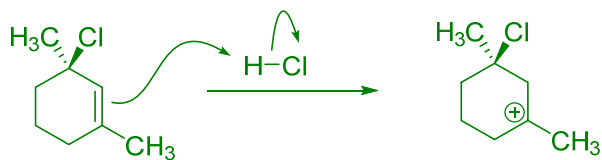
Recall that curved arrows show how the electrons in the reactants are redistributed to form the product at the end of the step. The arrows point from the source to their final destination. Here, the electron pair in the C=C  $\pi$  bond is used to form a bond to the hydrogen atom in H-Cl. The electron pair associated with HCl is given to the chlorine atom, making  $\text{Cl}^-$  as another product.

Where you've seen it: Fall 2017 Lecture 14 in-class problem on Slide 5.

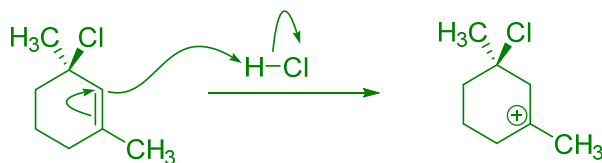
Grading and partial credit:

+1 per correct arrow, -1 each additional incorrect arrow

Full points:

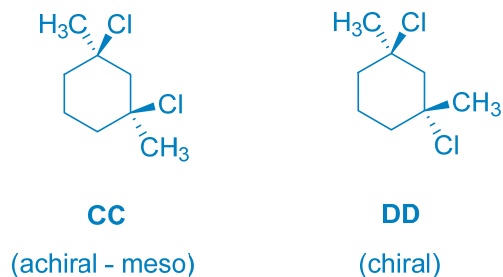


+1 point:



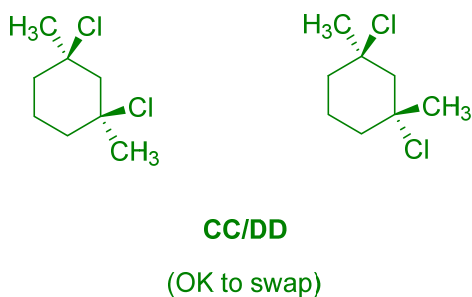
(2) **BB** then goes on to react with chloride to produce two major products, **CC** and **DD**. In the boxes on your answer sheet, draw the structures of products **CC** and **DD**. It does not matter which you choose to be **CC** and which you choose to be **DD**.

In the second step, the chloride nucleophile can attack carbocation **BB** from either lobe of the vacant  $2p$  orbital on carbon (above or below the ring). We observe two corresponding products:



Where you've seen it: Fall 2017 Lecture 17 Slide 18.

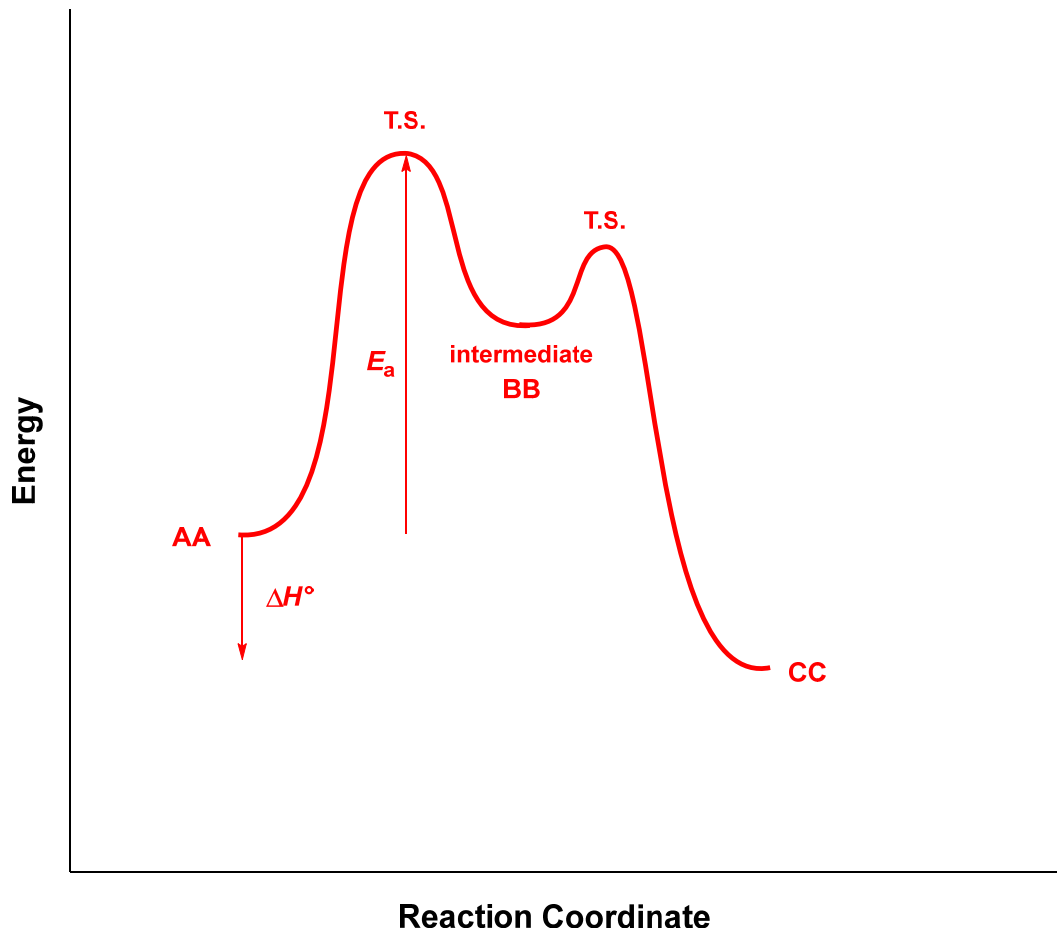
Full points:



+1 for correct product with ambiguous stereochemistry



- (3) Read carefully and follow all directions... Draw a reaction energy diagram of  $\Delta H^\circ$  (enthalpy) versus the progress of the reaction from **AA** to **CC** on the set of axes found on your answer sheet. Explicitly label the  $\Delta H$  for the reaction (on your plot) as well as the activation energy ( $E_a$ ) for the rate-determining step. Explicitly label where **BB** is on your graph. Also label any transition states as "T.S.". You do not need to draw the Lewis structure of any transition state or intermediate.



The mechanism has two steps: (i) protonation of the alkene to generate carbocation **BB** and (ii) attack of chloride to generate the products. Thus, we will have two transition states (peaks) and one reactive intermediate state (a high local minimum). The first step is rate-determining (generation of the relatively unstable carbocation), so it will have the higher activation energy. Overall, the reaction is exothermic. You are breaking a C=C  $\pi$  bond (611–350 kJ/mol) and the H–Cl (432) bond and forming new C–H (410) and C–Cl (330)  $\sigma$  bonds for a net  $\Delta H^\circ = -47$  kJ/mol.

Identical format to Fall 2016 Exam #2 Problem III-3, Fall 2015 Quiz #3 Problem II-1.

Grading and partial credit:

- +2 for each correctly identified transition state
- +1 for intermediate labeled as **BB**
- +1 for activation energy of rate-determining step labeled correctly
- +1 for  $\Delta H$  labeled correctly
- +1 for correctly labeling reaction as exothermic (by relative position of reactants and products)

(4) (2 points) On your answer sheet, circle the term that best describes the relationship between **CC** and **DD**.

diastereomers

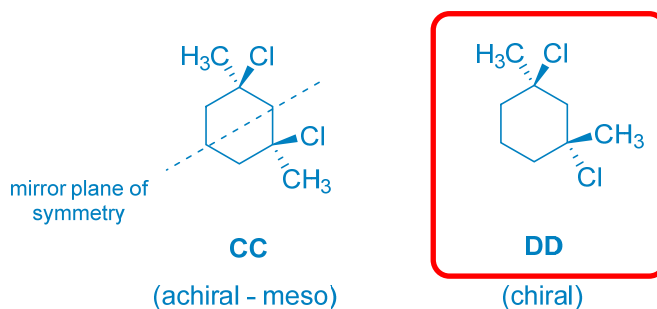
enantiomers

conformers

constitutional Isomers

+2 if circled term correctly corresponds to structures drawn in Part 2 (i.e., if structures **CC** and **DD** are incorrect but student correctly identified the relationship between the incorrect structures drawn)

(5) (2 points) On your answer sheet, go back to Part (2) and circle your drawing of **CC** and/or **DD** if each is optically active. If either compound is not optically active, leave it uncircled.



**CC** is achiral; **DD** is chiral.

Where you've seen it: Extensive problems on definitions of chirality, enantiomer, diastereomer, etc.

Grading, for each structure drawn in Part 2:

+1 if circled structure is chiral or uncircled structure is achiral, even if the answer in Part 2 is incorrect (i.e., if structure **CC** is incorrect but student correctly identified the incorrect structure as chiral or achiral)

**Problem IV.** Explanation (6 points). Consider the following two molecules.



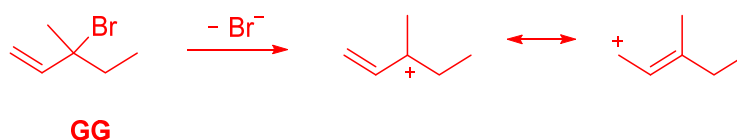
(1) Which substrate, **FF** or **GG**, will react fastest in a solvolysis reaction with methanol to form an ether as a product? Write the letter of your answer in the box on the answer sheet (3 points).

Compound **GG** will react faster. (+3 points, all or nothing)

(2) In two sentences and relevant drawings, use the Hammond Postulate to justify your choice (3 points).

A solvolysis reaction is a substitution reaction in which some of the solvent molecules react as nucleophiles. It is most commonly encountered for  $S_N1$  reactions.

The Hammond Postulate states that for an endothermic process, anything that stabilizes the products will stabilize the transition state and increase the rate of the reaction. Resonance stabilization helps to stabilize the carbocation formed by **GG**.

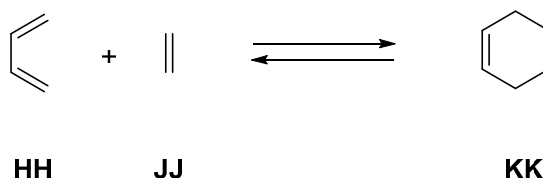


Where you've seen it: Essentially identical to Fall 2015 Quiz #3 Problem IV-2. Similar to Summer 2016 Exam #2 Problem IV-1, Fall 2015 Quiz #3 Problem IV-1. The term 'solvolysis' was highlighted in bright orange and defined on a Fall 2017 Lecture 17 slide, but you didn't need to know that term as you are told the product is an ether, which here could only result from the attack of methanol.

Grading and partial credit:

- +3 for "The Hammond Postulate states that for an endothermic process, anything that stabilizes the products, will stabilize the transition state and increase the rate of the reaction. Resonance stabilization helps to stabilize the carbocation in **GG**." Drawings of resonance forms must be included for full credit.
- +2 for saying the **GG** is resonance stabilized but there are no drawings, or drawings are incorrect
- +1 for invoking the Hammond Postulate but stating that hyperconjugation is the reason for the stabilization
- +1 for stating the Hammond Postulate without any other errors
- 1 for incorrect Hammond Postulate if any points were previously awarded for above

**Problem V.** Explanation (6 points). Consider the temperature dependence of the Diels–Alder reaction of ethylene (**JJ**) and 1,3-butadiene (**HH**):



At 200 °C, the equilibrium favors the product's side (right), while at 900 °C, the equilibrium favors the reactants' side (left). Briefly explain the reason for this difference using the relation:

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

Ref: <https://www2.chemistry.msu.edu/faculty/reusch/virttxtjml/enrgtop.htm>

The change in enthalpy will be determined primarily by the bonds that are being made and broken. In this reaction, 3 carbon–carbon  $\pi$  bonds in the starting materials are being converted to 1 carbon–carbon  $\pi$  bond and 2 carbon–carbon  $\sigma$  bonds in the product. Since  $\sigma$  bonds are stronger than  $\pi$  bonds, this reaction is clearly exothermic ( $\Delta H^\circ$  is negative), but you can go ahead and run the Hess's Law calculation using the bond energy table to confirm. We expect the reaction to have  $\Delta S^\circ < 0$ , since two molecules in the starting materials are being converted to a single product molecule.

For this reaction,  $\Delta H < 0$  (favorable) and  $\Delta S < 0$  (unfavorable). The overall favorability of the reaction is governed by  $\Delta G$ , the change in free energy. As  $\Delta G = \Delta H - T\Delta S$ , we expect the enthalpy term to dominate at (relatively) low temperature and the entropy term to dominate at high temperature. Since  $\Delta S < 0$  (unfavorable) we expect  $\Delta G$  to become increasingly positive (unfavorable) as temperature increases, so the reactants' side will be favored at high temperature.

Where you've seen it: This question is a free-response version of the Fall 2017 Quiz #2 Questions 13 and 14, which used the same (Diels–Alder) reaction and explanation. Also resembles Fall 2016 Exam #2 Problem I-19.

Grading:

- +2 for saying  $\Delta H$  is negative
- +2 for saying  $\Delta S$  is negative
- +2 for saying that the  $T\Delta S$  term dominates at high temperatures
- 1 for each additional erroneous statement


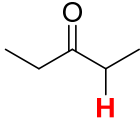

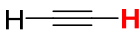
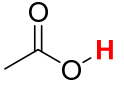

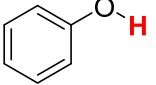

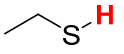
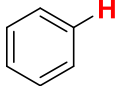
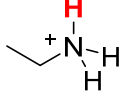


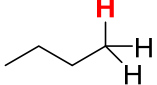
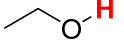
Partial Credit (applied if no credit is granted from above funnel, with +1 as a maximum)

- +1 for saying that  $\Delta G$  is negative if equilibrium favors products
- +1 for saying as temperature increases,  $\Delta G$  increases
- +1 for any discussion of Le Châtelier's principle (which, by the way, does not apply here because the equilibrium is not just shifting to accommodate the extra heat)

1		2									
H	He										
hydrogen 1.008		helium 4.003									
3	4	10									
Li	Be	Ne									
lithium 6.94	beryllium 9.01	neon 20.180									
11	12	18									
Na	Mg	Ar									
sodium 22.990	magnesium 24.305	argon 39.948									
19	20	36									
K	Ca	Kr									
potassium 39.098	calcium 40.078	krypton 83.798									
37	38	54									
Rb	Sr	Xe									
rubidium 85.468	strontium 87.62	xenon 131.29									
55	56	86									
Cs	Ba	Rn									
cesium 132.91	barium 137.33	radon (222)									
87	88	118									
Fr	Ra	Og									
francium (223)	radium (226)	oganesson (294)									

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
<b>La</b> lanthanum 138.91	<b>Ce</b> cerium 140.12	<b>Pr</b> praseodymium 140.91	<b>Nd</b> neodymium 144.24	<b>Pm</b> promethium (145)	<b>Sm</b> samarium 150.36	<b>Eu</b> europium 151.96	<b>Gd</b> gadolinium 157.25	<b>Tb</b> terbium 158.93	<b>Dy</b> dysprosium 162.50	<b>Ho</b> holmium 164.93	<b>Er</b> erbium 167.26	<b>Tm</b> thulium 168.93	<b>Yb</b> ytterbium 173.05	<b>Lu</b> lutetium 174.97
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
<b>Ac</b> actinium (227)	<b>Th</b> thorium 232.04	<b>Pa</b> protactinium 231.04	<b>U</b> uranium 238.03	<b>Np</b> neptunium (237)	<b>Pu</b> plutonium (244)	<b>Am</b> americium (243)	<b>Cm</b> curium (247)	<b>Bk</b> berkelium (247)	<b>Cf</b> californium (251)	<b>Es</b> einsteinium (252)	<b>Fm</b> fermium (257)	<b>Md</b> mendelevium (258)	<b>No</b> nobelium (259)	<b>Lr</b> lawrencium (260)

**pK<sub>a</sub> Table**

	-8.0		19-20
	-1.7		25
	4.8		36
	10.0		38
	10-11		43
	10.6		44
	15.7		~50
	15.9		

## Bond Dissociation Energies (BDEs)

Average Bond Dissociation Energies, $D$ (kJ/mol) <sup>a</sup>											
H—H	436 <sup>a</sup>	C—H	410	N—H	390	O—H	460	F—F	159 <sup>a</sup>		
H—C	410	C—C	350	N—C	300	O—C	350	Cl—Cl	243 <sup>a</sup>		
H—F	570 <sup>a</sup>	C—F	450	N—F	270	O—F	180	Br—Br	193 <sup>a</sup>		
H—Cl	432 <sup>a</sup>	C—Cl	330	N—Cl	200	O—Cl	200	I—I	151 <sup>a</sup>		
H—Br	366 <sup>a</sup>	C—Br	270	N—Br	240	O—Br	210	S—F	310		
H—I	298 <sup>a</sup>	C—I	240	N—I	—	O—I	220	S—Cl	250		
H—N	390	C—N	300	N—N	240	O—N	200	S—Br	210		
H—O	460	C—O	350	N—O	200	O—O	180	S—S	225		
H—S	340	C—S	260	N—S	—	O—S	—				
<b>Multiple covalent bonds</b>											
C=C	611	C≡C	835	C=O	732	O=O	498 <sup>a</sup>	N≡N	945 <sup>a</sup>		

<sup>a</sup> Exact value

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Exam Booklet No.