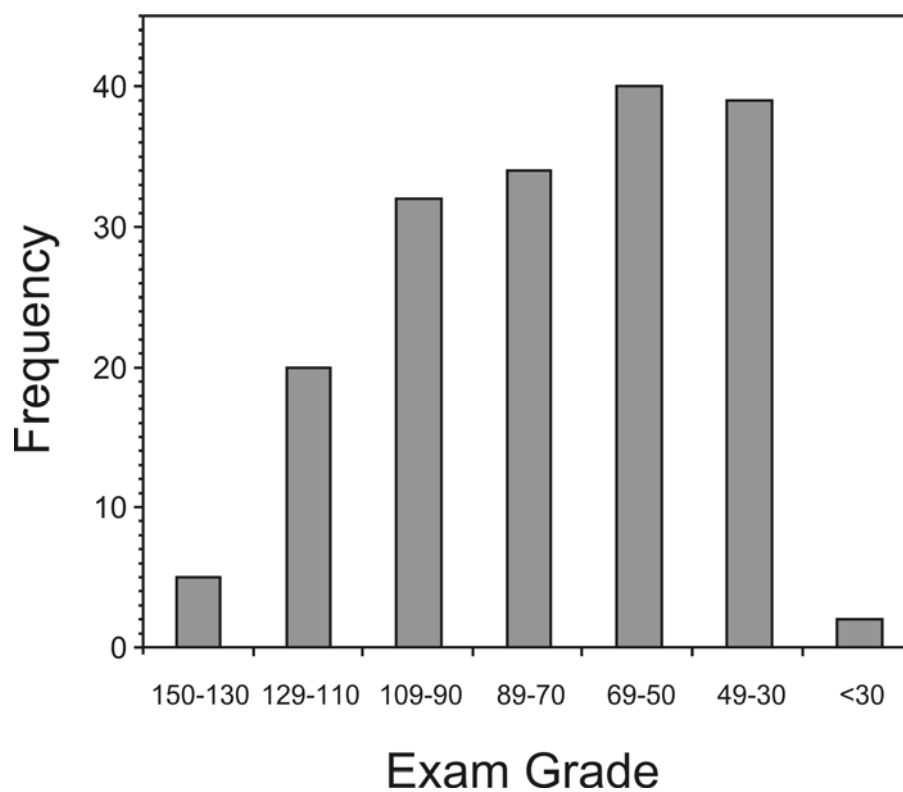
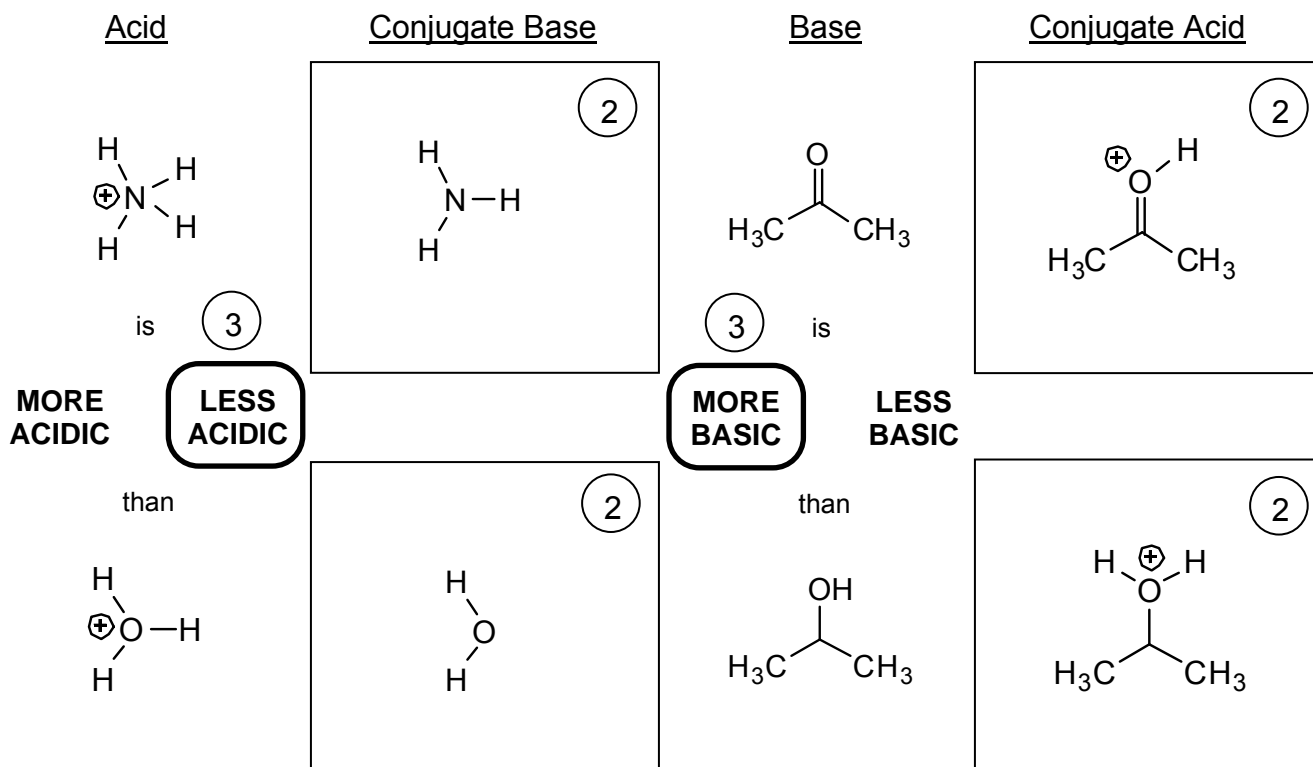


**Final Exam
Answer Key**

Final Exam Mean: 77
Final Exam Median: 75
Final Exam St. Dev.: 28



1. (14 pts) For each of the pairs of acids (or bases) below,
- Draw the conjugate base (or acid).
 - Circle whether you think the first acid (or base) is more or less acidic (or basic) than the second.



The two starting acids are ions, and their relative acidity will depend on the relative stability of the charges. Nitrogen is less electronegative than oxygen, so the positive charge is more stably accommodated at nitrogen. That makes nitrogen less likely to give up the charge, and the first acid less acidic.

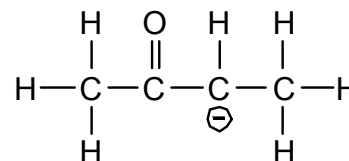
Of the cations on the right, the upper cation is stabilized by resonance, but the lower one is not. Because the upper cation is more stable, the upper base that produces it is more basic.

Rubric:

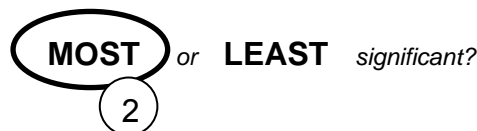
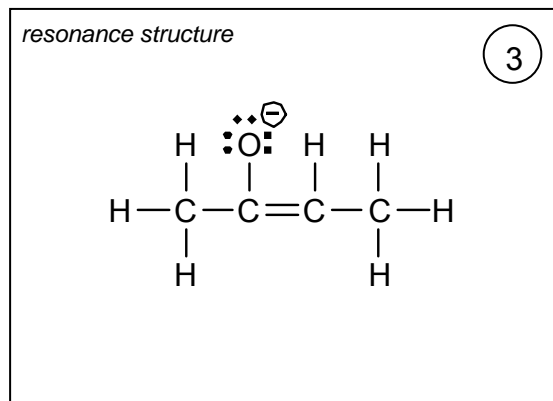
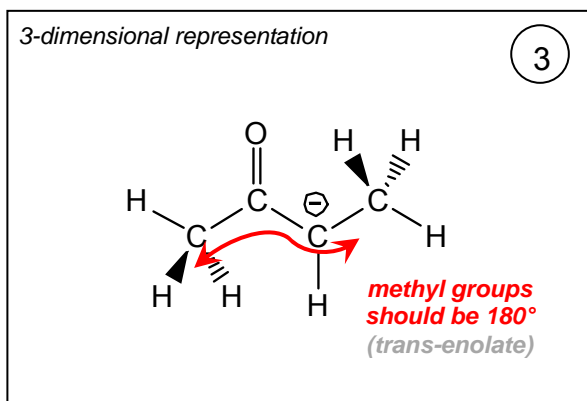
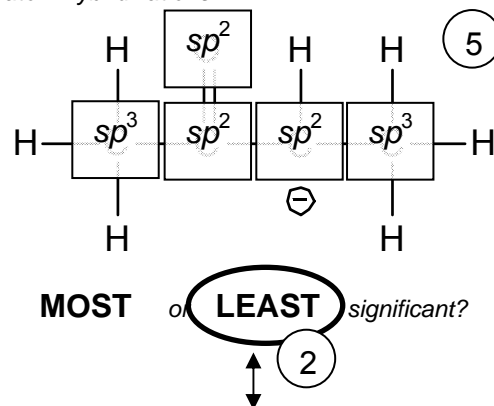
- 2 points per conjugate acid/base structure. *No partial credit.*
- 3 points per circled more/less acidic/basic.

2. (15 pts) For the anion drawn at right, in the boxes provided:

- Draw all significant resonance structures. In each structure, draw all atoms, bonds, lone pairs of electrons, and formal charges. Then, circle which resonance structure you think is the most significant, and which is the least. **Circle only one MOST and one LEAST.**
- Draw a Lewis wedge/dashed-bond structure that illustrates the most stable three-dimensional conformation of the molecule. Draw all atoms, bonds, and charges, but omit lone pairs.
- In the boxes provided, write the hybridization state on any atom heavier than hydrogen.



atom hybridizations:



Rubric:

-1 point for each trivial mistake in structure (left out an H, extra C, etc.)
 Hybridizations: 1 point each. (5 points this part.)

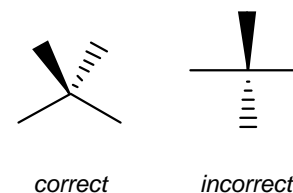
3-D drawing: 3 points total.

1 point for flat enolate. (No groups in or out of molecule plane in the center.)
 1 point for *anti* (180°) dihedral angle for methyl groups.

Anti conformation puts the largest groups farthest away from each other.

1 point for illustrating tetrahedral carbons correctly.

Tetrahedral centers are illustrated as having two bonds in the plane of the page on one side of the center, and two bonds out of the plane (one forward, one back) on the other side.



Resonance structures: 3 points each.

1 point for formal charges (both charges must be correct).

1 point for lone pairs (all must be correct).

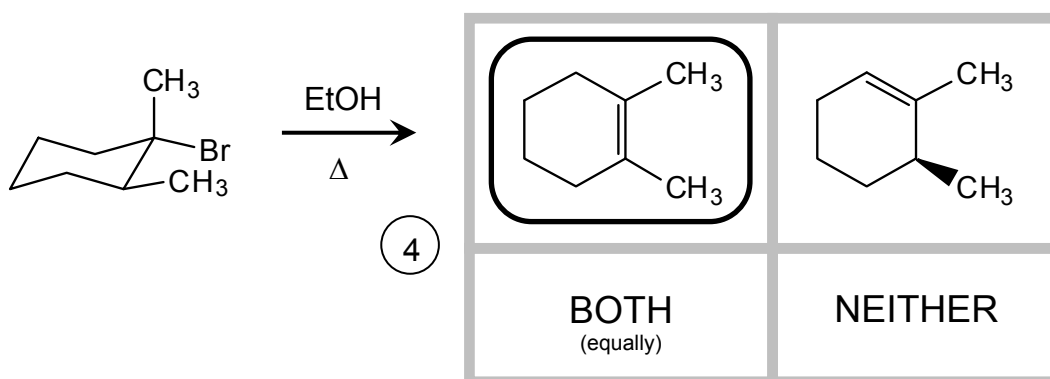
1 point for bonds (all must be correct).

Resonance structures need not be in 3-D, or have correct bond angles.

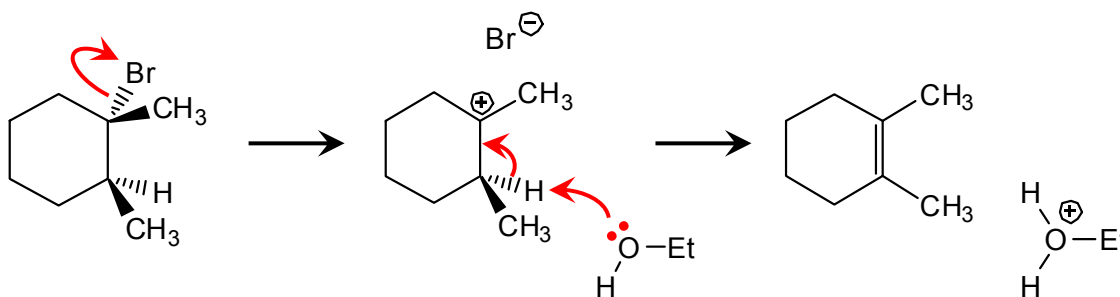
Contributions (MOST/LEAST): 4 points for both correct. (2 points each.)

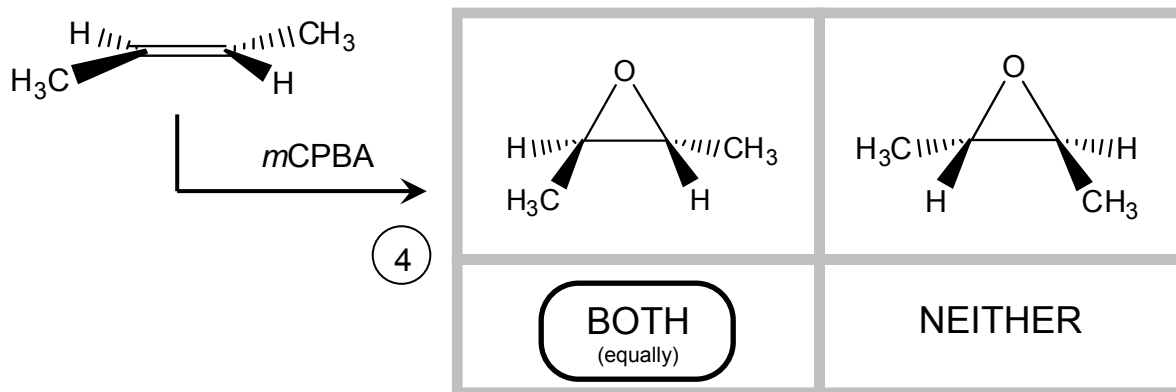
If you circle the same answer for both, no credit.

3. (12 pts) Each of the reactions below and on the next page is drawn with two possible products. If one of the two products predominates, circle that preferred product. If the two products are produced equally, circle "BOTH". If neither product would result from the reaction, circle "NEITHER". **Circle one answer only.**

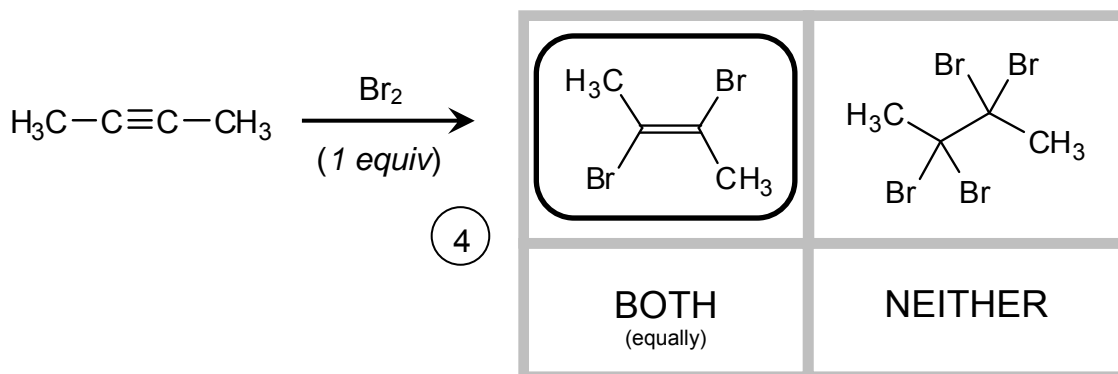
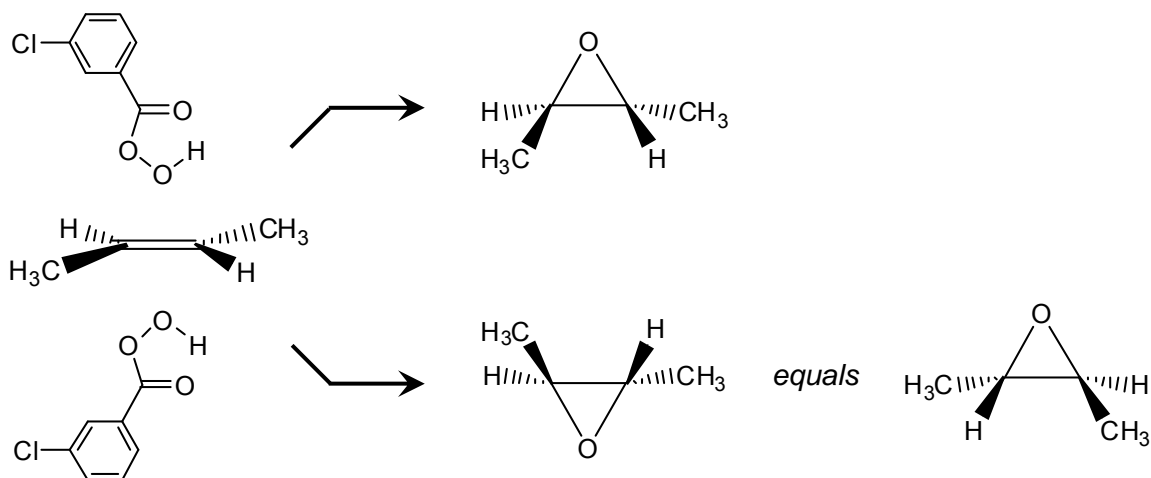


These conditions—a weak base (EtOH) and heat—correspond to E1 elimination conditions. E1 elimination, unlike E2, does *not* have the requirement that the leaving group and the proton being removed be anti-coplanar. Instead, because the reaction passes through a planar cation intermediate, the incoming base is free to take the proton that leads to the most stable alkene product. In this case, that most stable product is the tetrasubstituted alkene on the left.



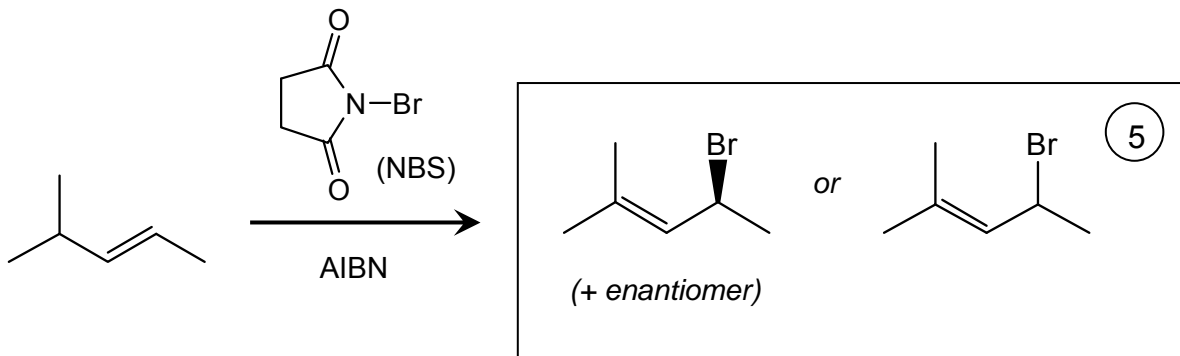


meta-Chloroperoxybenzoic acid (mCPBA) can transfer a single oxygen atom to either the top or bottom face of the starting alkene, to generate each of the two products shown above in equal amounts:

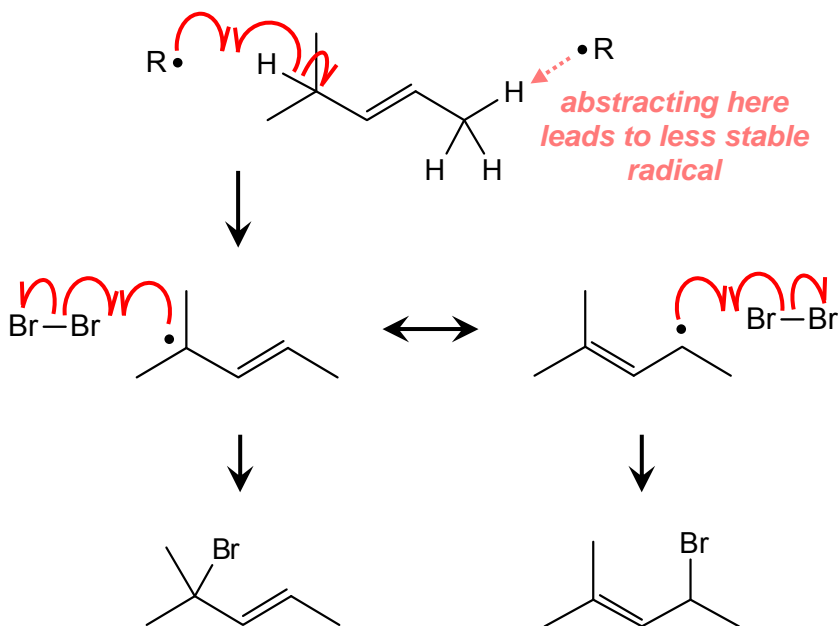


Adding one molecule of Br_2 to the alkyne makes the resulting alkene less willing to donate electrons to a second molecule of Br_2 . So the reaction stops reliably at the mono-adduct.

4. (15 pts) For each of the reactions on the following pages, fill in the empty box corresponding to the major product. Wherever appropriate, illustrate stereochemistry in your drawings (using wedge and dashed bonds). If multiple enantiomers or diastereomers are produced, indicate this in the answer box (e.g., by writing “+ enantiomer”, etc.)



NBS is a reagent that accomplishes allylic (or benzylic) radical bromination, by abstraction of an H adjacent to a double bond, followed by reaction of the resulting allylic radical with Br_2 . There are two H's that could, in principle, be abstracted, but the taking the tertiary H will lead to the more stable radical, and will be favored.



Neither of the two radical structures shown above is any more stable than the other; they are resonance structures, or just two ways of drawing the same structure, so they have the same energy. As a result, the usual criterion that we would use to predict product distributions in radical halogenations—relative stability of the intermediate radicals—cannot be used to distinguish these two products, because

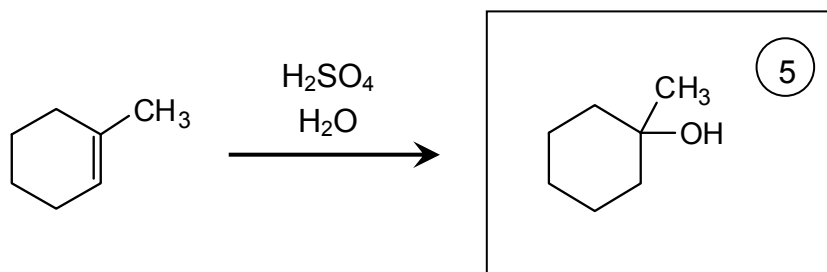
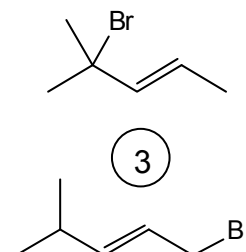
they come from the same radical. That isn't to say, however, that the two products are made equally. The more highly substituted alkene, the product on the right, would be more stable than the product on the left. Hammond's postulate tells us that this product, as a result, should be favored.

Rubric:

5 points for correct structure.

We didn't grade stereochemistry on this problem. If you didn't illustrate stereochemistry, you still got full credit.

3 points partial for allylic halogenation without generating most stable alkene product.



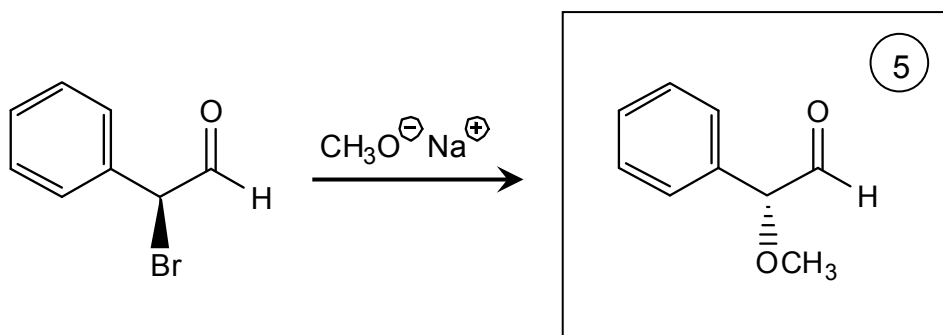
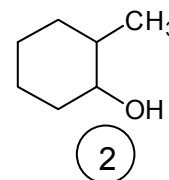
These are the conditions for Markovnikov hydration (addition of H-OH) onto the alkene. The -OH group ends up on the more substituted carbon.

Rubric:

5 points for correct structure.

Illustrating in 3-D was fine, but unnecessary; the product has no stereocenters.

2 points partial for anti-Markovnikov addition (any stereochemistry)



Normally, CH_3O^- would react with an alkyl halide via E2 elimination to generate an alkene. However, in this case, there is no available proton on any carbon one carbon away from the leaving group, a requirement of elimination. True, there is the aldehyde H, but that's attached to an sp^2 -hybridized center, and E2 does not occur at sp^2 -hybridized centers. So, this reaction occurs via $\text{S}_{\text{N}}2$.

Rubric:

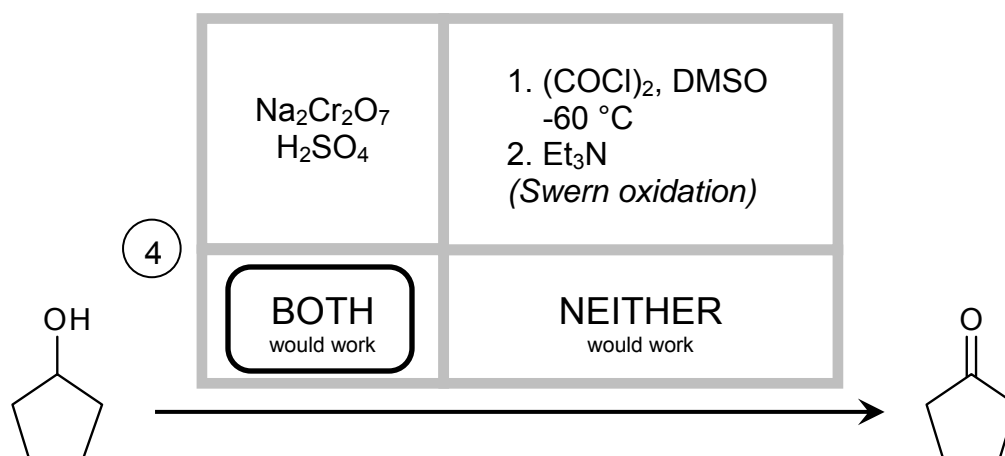
5 points for correct structure.

4 points partial for writing "+ enantiomer". Reaction is stereospecific.

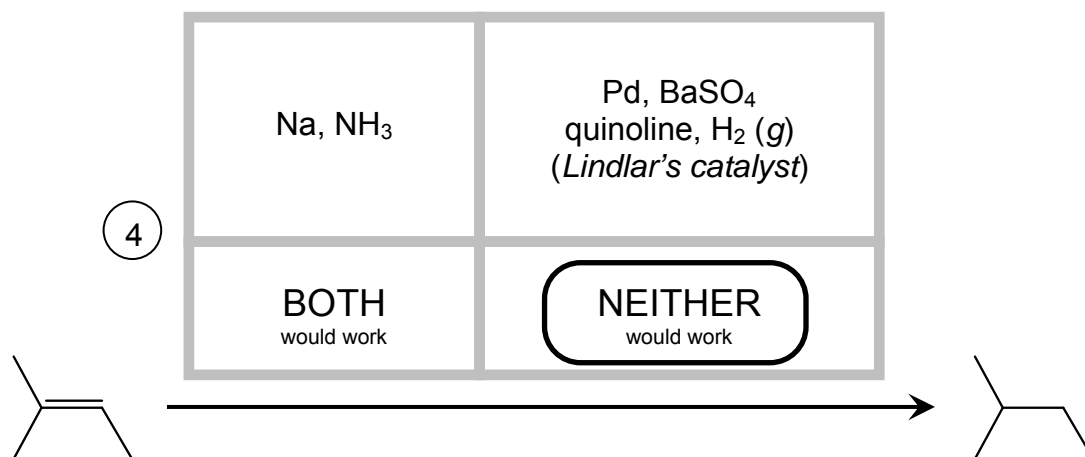
3 points partial for incorrect stereochemistry, or for not indicating stereochemistry.

(You won't lose a point for including "+ enantiomer" here—still 3 points.)

5. (8 pts) Each of the reactions below is drawn with two possible reaction conditions. If only one of the two reaction conditions would generate the given molecule as the major product, circle those conditions. If both sets of conditions would accomplish the reaction, circle "BOTH". If neither set of reaction conditions would succeed, circle "NEITHER". **Circle one answer only.**

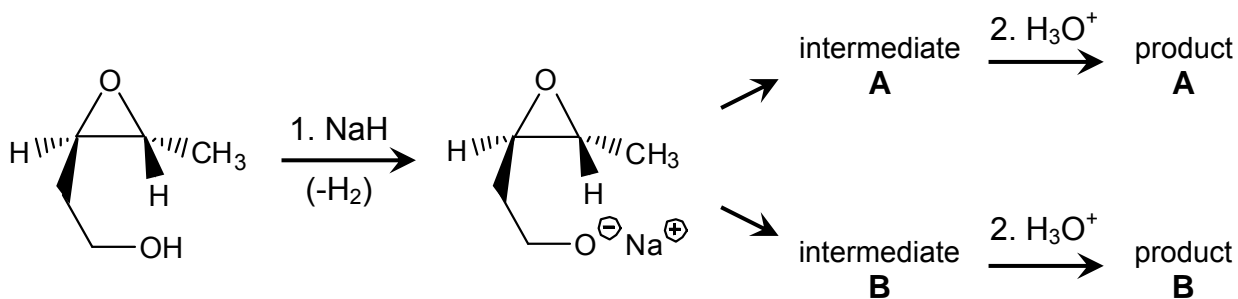


Both of these synthesis protocols accomplish oxidation. The first, chromate oxidation, will oxidize anything as far as it can be oxidized (without breaking C-C bonds). The secondary alcohol starting material can only be oxidized to a ketone, so chromate will accomplish this oxidation. The second protocol, Swern oxidation, will only oxidize an alcohol to an aldehyde or ketone. That's exactly what's happening here, so the second protocol will work too.



Both of the reagent systems given reduce alkynes to alkenes and then stop. Neither of them will reduce alkenes to anything.

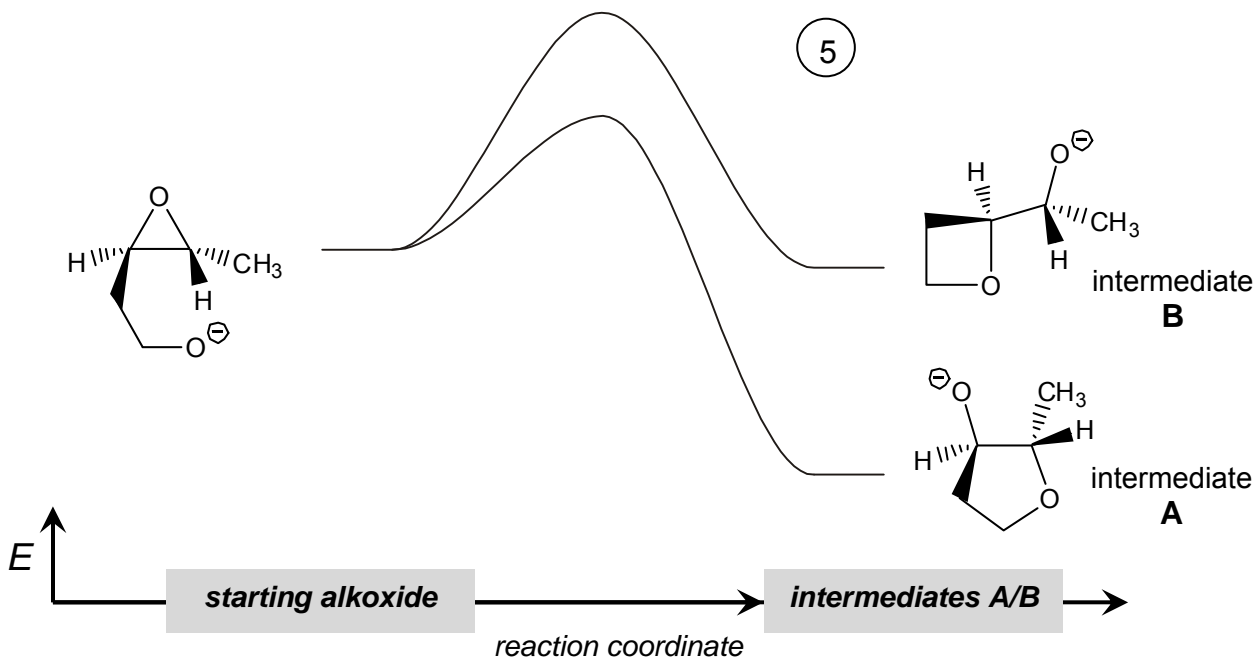
6. (25 pts) When the epoxide-alcohol starting material below is deprotonated with NaH, the resulting alkoxide reacts with itself to open the epoxide. That reaction, followed by acidic workup, can produce two different products; the difference between the products is dictated by which epoxide carbon is attacked by the alkoxide.



In this problem, we will name the products **A** and **B**, which are formed by protonation of intermediates **A** and **B**.

- (a) Using “electron pushing”, draw a mechanism that illustrates the formation of intermediates **A** and **B** from the alkoxide. I’ve drawn the starting material for you—just add curved arrows to my structure. Then, draw the structures of intermediate **A** and intermediate **B**. Wherever appropriate, illustrate stereochemistry.





Rubric for part (c): (5 points total this part.)

*You didn't need to draw product structures, but you did need to make clear which curve went to **A** and which to **B**.*

1 point for correctly ordering intermediates **A** and **B** on the diagram.

Correct order depends on answer to (a). If (b) was incorrect, it seems unlikely you will get this point.

1 point for each path having just one hump.

1 point for different transition state energies that match product energies.

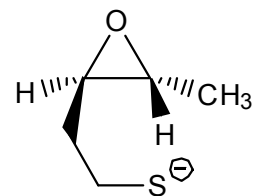
(Hammond's postulate applies here.)

1 point for both reactions being exothermic.

1 point for cyclobutane formation being close to thermoneutral.

*(I.e., energy difference between starting material and intermediate **B** should be less than difference between intermediates **A** and **B**.)*

(d) How would the rate of the two reactions be affected if the starting material were a thiol instead of an alcohol? Assume that the thiolate on the right has the same energy as the alkoxide above, and that the sulfur-containing intermediates **A_S** and **B_S** are also the same energy as intermediates **A** and **B**. Would the thiolate react



FASTER
than

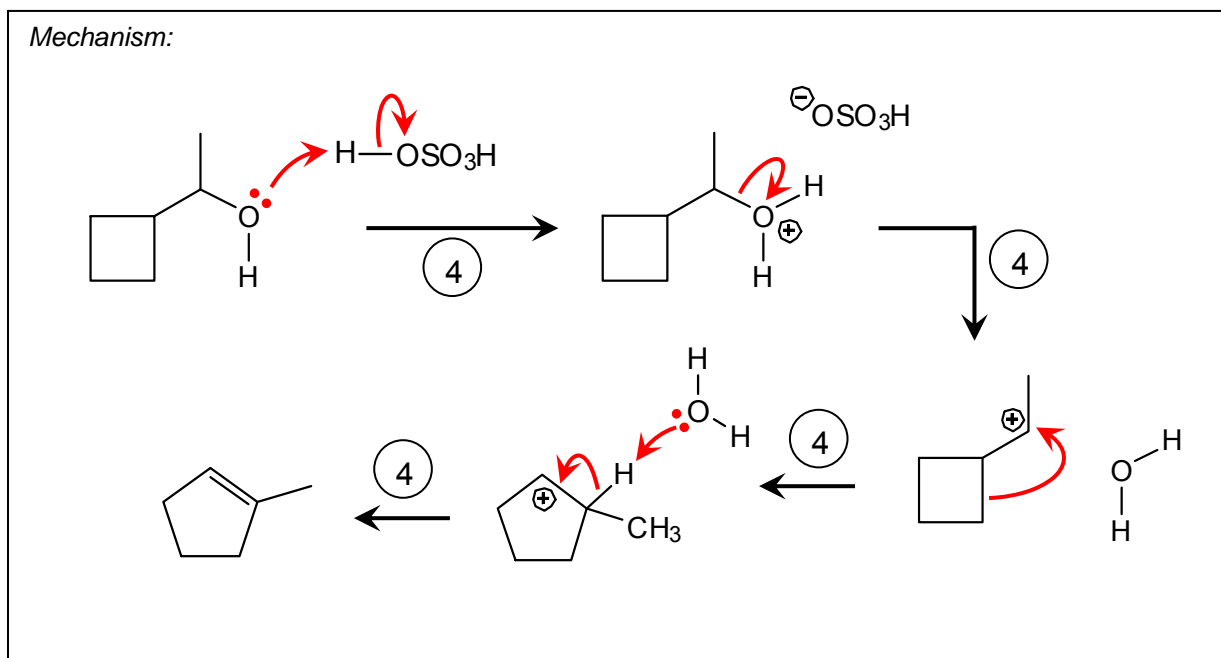
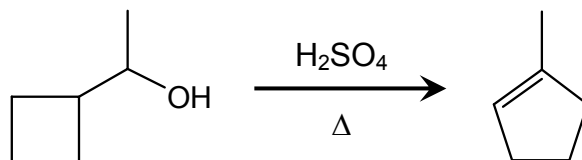
3

SLOWER
than

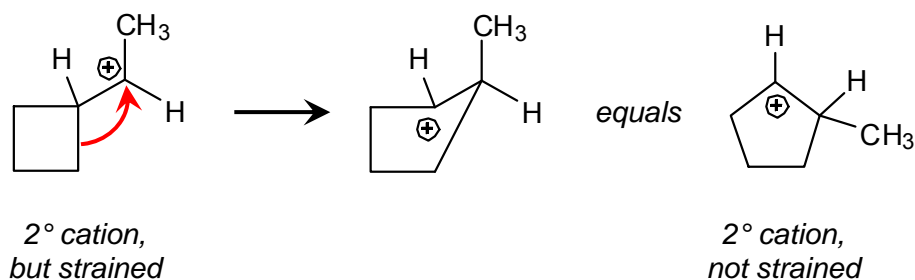
the
SAME RATE
as

the alkoxide?
(Circle one.)

7. (16 pts) Draw a mechanism (using “electron pushing”) for each of the reactions shown below. Draw each mechanistic step explicitly; don’t cheat by combining multiple processes in a single step. Use only the molecules shown in the problem; don’t invoke generic species. (E.g., don’t use “H-A” as a generic acid.)



The conditions given correspond to a typical E1 elimination reaction, and sure enough a leaving group leaves to create an alkene in the product. But something else is clearly going on here, in that the hydrocarbon backbone is rearranged in the product. A 1,2-alkyl shift happens here to relieve the strain in the cyclobutane ring:



Rubric: (16 points total this part)

Overall notes:

Must be these steps, in this order.

Overall, the minimum score for each step is zero; errors in a step cannot earn you negative points that count against another, correct step.

Things that have left (e.g., $^-OSO_3H$) and spectators may be omitted.

-2 points, for each arrow in each step, for errors in drawing arrows. Arrow must start at an electron pair, and end at nucleus or bond where electrons will newly interact.

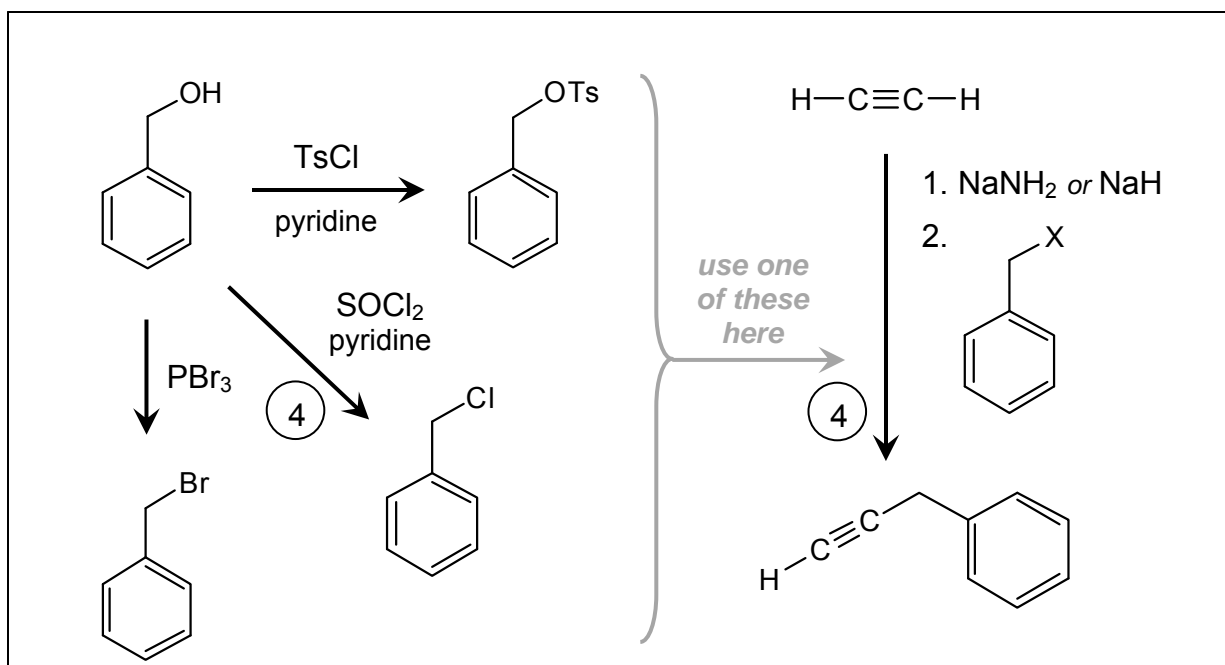
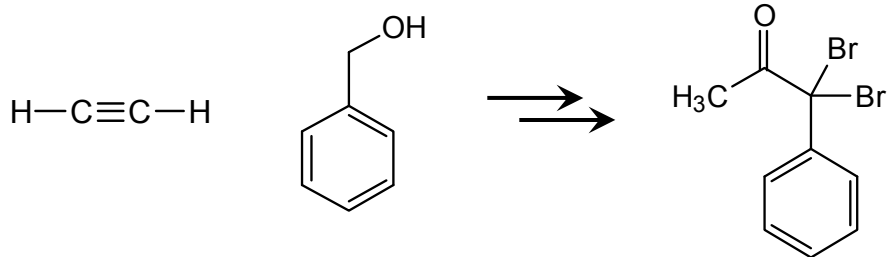
-2 points for each error in charge, valency, structure, base, etc.; if error propagates, points are taken off only for initial error.

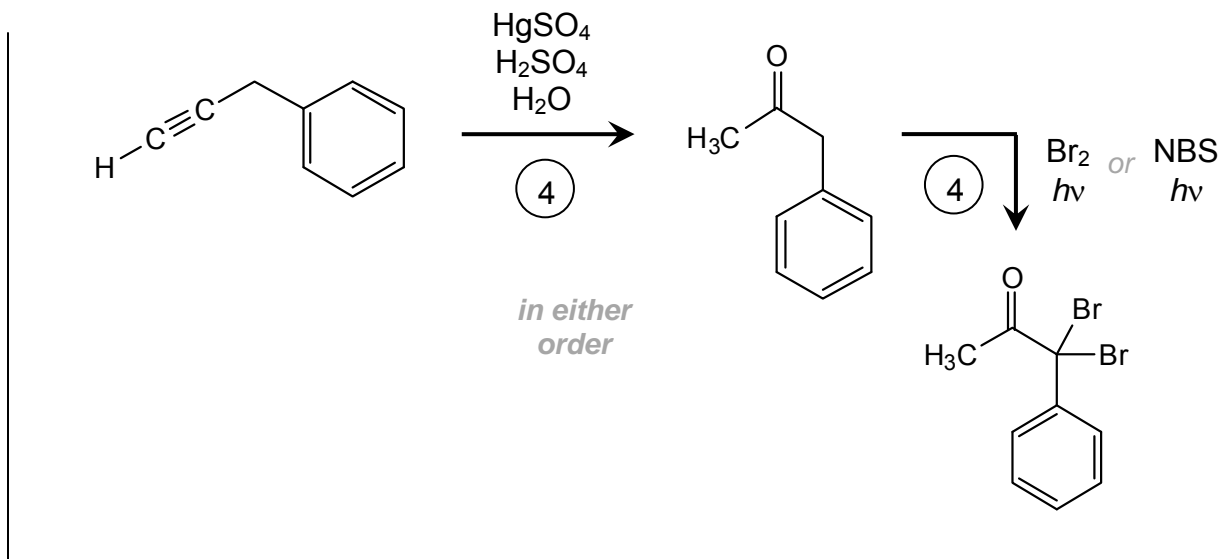
-4 points (out of 8) for combining two steps into one.

4 points per step.

2 points (out of 8) for beginning mechanism with ^-OH as leaving group. This substitutes for first 2 steps.

8. (16 pts) For each set of starting materials and products shown below, **propose a multistep synthesis**. In addition to the molecules shown, you can use any reagents and reactions we've learned about in class. You might discover multiple answers to this problem; draw only your best (one) synthetic route. Feel free to draw an incomplete route—we will give you partial credit where we can.





This synthesis required 4 tasks, and there were some limitations to the order you did them in.

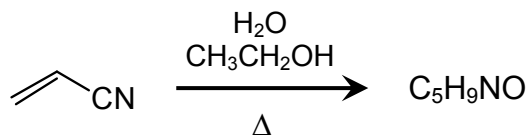
- 1. Convert benzyl alcohol into something with a good leaving group** (like a tosylate or halide) that is compatible with an alkynyl anion. There are many ways to do this, and we accepted all of them (including HBr or HCl, not shown above). This must be done, because benzyl alcohol would just transfer a proton to an alkynyl anion.
- 2. Generate an alkynyl anion, and combine it with the electrophile from step 1.**
- 3. Convert the alkyne to a ketone.** This could be done directly via Markovnikov hydration (as I've shown above). But some of you chose to hydrogenate the alkyne to the alkene, hydrate to the alcohol, and then oxidize the alcohol to the ketone, and though this would be the long way, we still gave that route credit.
- 4. Halogenate the benzylic position twice.** This would happen naturally if you ran a bromination reaction (using Br₂ or NBS) long enough, or you could sequentially add single bromine atoms; we didn't care, as long as the bromination would work. You could also switch steps 3 and 4.

Rubric: (14 points total this part)

General notes:

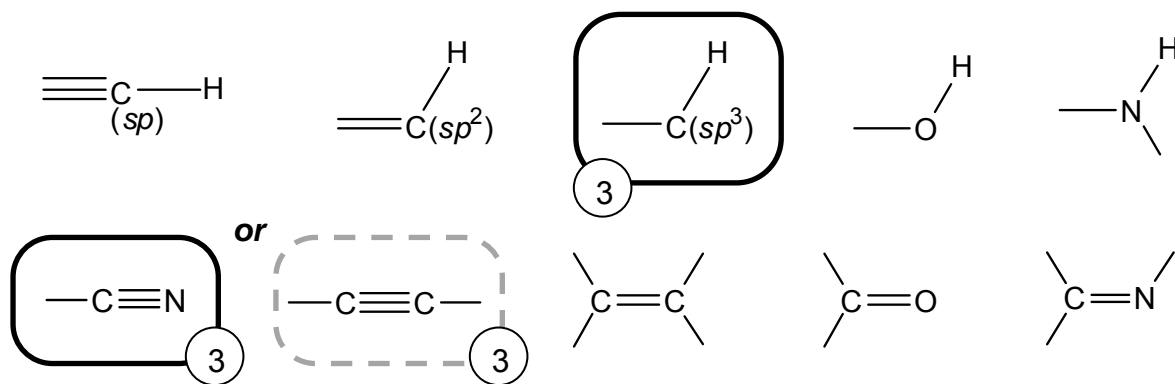
- 1 point for each minor error in structures or reagents; if error propagates, points are taken off only for initial error.
 - 2 points if step reagents are incorrect, but reaction could otherwise be accomplished with correct reagents.
 - 2 points if reagents are correct, but product is wrong. If this happened, and you were led down an incorrect synthetic path by your mistake, you can also lose later points.
- 4 points for each element.

9. (29 pts) Acrylonitrile, the starting material on the right, can be polymerized into polyacrylonitrile (a component of plastic consumer goods) by heating it in solvent, but heating acrylonitrile in a mixture of ethanol and water generates a small molecule product instead. This product was isolated and characterized by NMR and IR spectroscopy and mass spectrometry; the spectra of this product are shown on the next two pages. High-resolution mass spectrometry determined an exact mass of 99.06840 amu for the highest-mass (parent, M^+) peak in the MS spectrum, which corresponds to a molecular formula of C_5H_9NO .



Before we answer any questions about the unknown molecule, this problem already tells us a couple of things. The molecular formula of our molecule changes from C_3H_3N to C_5H_9NO , which means that the molecule picks up two carbons, an oxygen, and some hydrogens, and it doesn't lose its nitrogen atom. The molecule gets substantially bigger, so something is clearly adding to this molecule. And our reaction conditions make it look like that something needs to come either from water, ethanol, or another molecule of starting material. (Given two carbons and an oxygen being added, my bet is on ethanol.)

- (a) Based on the features in the IR spectrum below, what functional groups would you expect the unknown molecule to have? **Circle all answers that apply.**



The IR spectrum really only has two important features: (1) no peaks above 2982 cm^{-1} , which indicates no $\text{C}(sp^2)-\text{H}$ or $\text{C}(sp)-\text{H}$ bonds; and (2) a peak at 2256 cm^{-1} , which the IR table tells us corresponds to either a $-\text{C}\equiv\text{N}$ or a $-\text{C}\equiv\text{C}-$ group. The starting material already has a $-\text{C}\equiv\text{N}$ group, so it seems likely that the reaction doesn't change the group that's already there. The starting material also has $\text{C}(sp^2)-\text{H}$ bonds which are gone in the product, so our reaction must be changing the alkene.

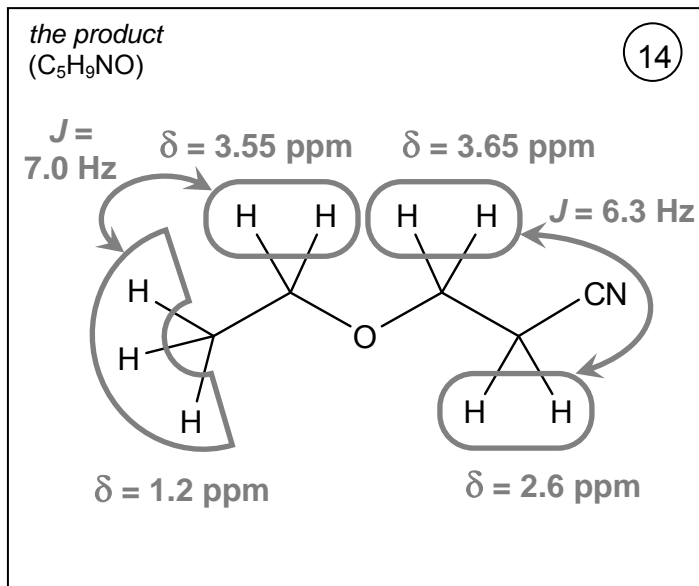
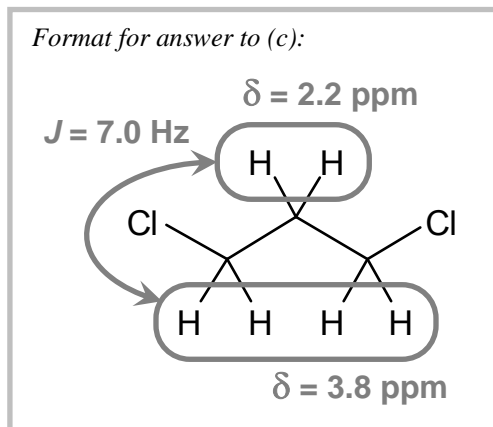
Rubric for part (a):

3 points for each correct circle.

-3 for each incorrect circle (up to 2; minimum score for this part is zero).

(c) **What is the structure of the product?** In the box on the next page, draw the molecule's structure, including all hydrogens. Then, considering the ^1H NMR spectrum,

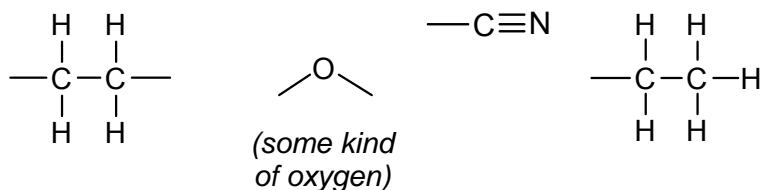
- Circle each group of equivalent H's;
- Assign a ^1H chemical shift (δ) to each circled group, within 0.05 ppm;
- Connect any pair of coupled, inequivalent groups of H's with a double-headed arrow, and then label that arrow with the corresponding coupling constant (J).



The NMR spectrum tells us that our unknown molecule must have four different (inequivalent) types of H's, and the coupling constants tell us that two out of the four are adjacent to each other, and the other two out of four are also adjacent. Graphically, our molecule must look like this:



All of these H's must be $\text{C}(\text{sp}^3)\text{-H}$'s (from the IR data), and there are only 4 carbons to support them. (The fifth is in the $-\text{CN}$ group.) That means our molecule probably has these pieces:



I think the only way to put these together is in the product structure above, which is the ethanol adduct of acylonitrile.

Rubric for part (c):

Structure need not be correct to receive points in this problem.

2 points for the correct molecule.

2 points for assigning each δ value. (8 points total.) To get 2 points, circle must include all equivalent protons for your structure, match the integration intensity of the peak, and match the type of proton that would appear at that frequency.

3.65, 3.55 ppm: Must be CH_n protons adjacent to an O.

1 point partial for assigning each ppm value to the wrong number of H's, or with the wrong number of neighbors. If multiple inequivalent H's are labeled with the same δ value, you get maximum 1 point partial credit for each δ value.

2.6 ppm: Must be two protons adjacent to CH_2O protons.

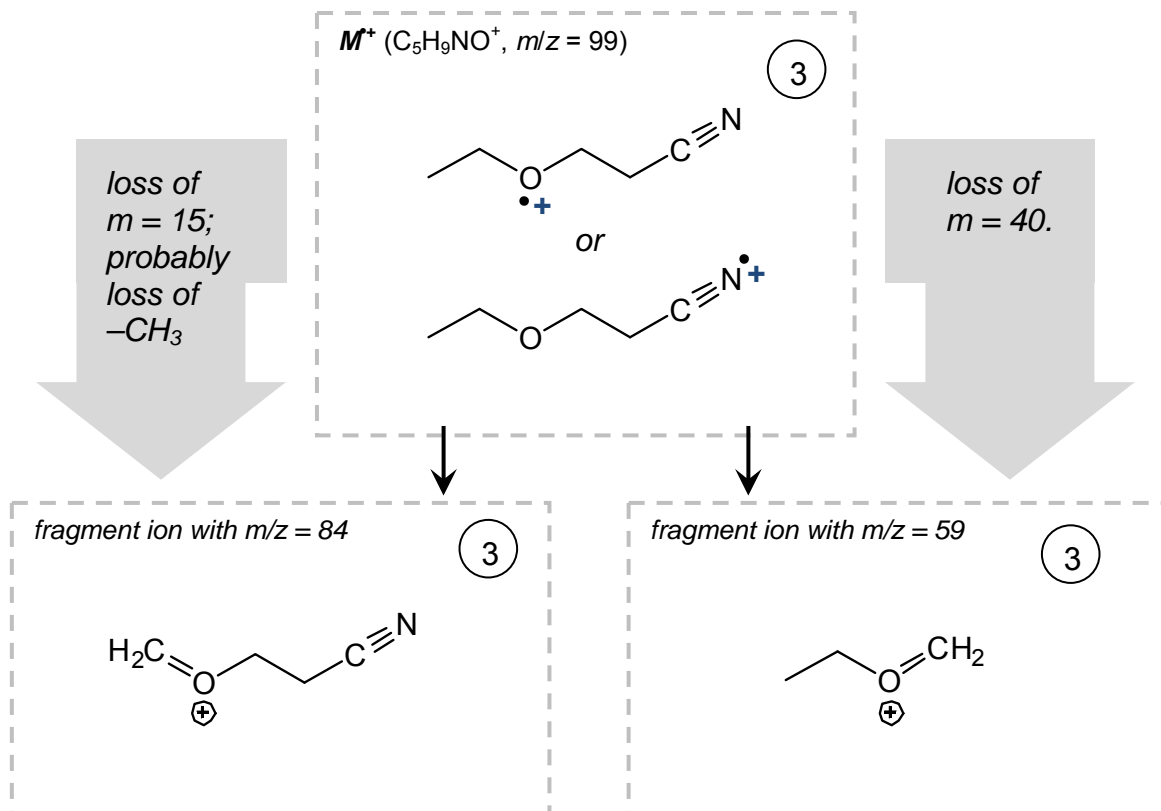
1.3 ppm: $-\text{CH}_3$ group that is part of an ethyl fragment.

1 point partial if methyl group has no neighboring H's, or the wrong number.

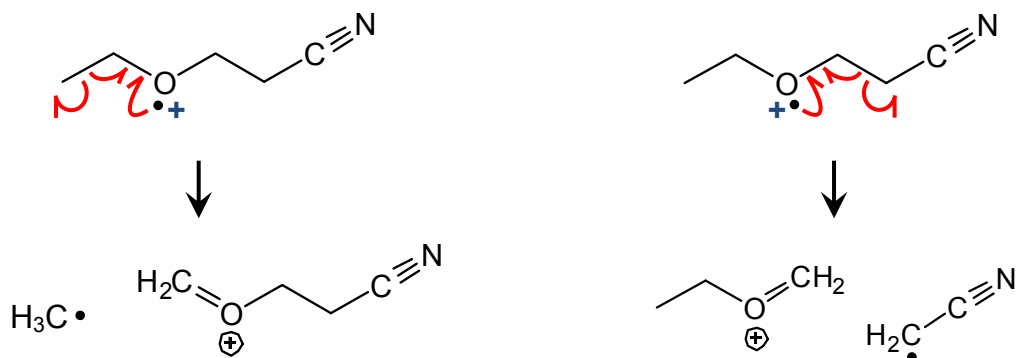
2 points for each J assignment (4 points total.)

Circles need not be correct to get these points, but shift assignments of coupled protons must be. Curved arrow only needs to connect one proton with an adjacent partner.

- (d) In an electron-ionization (EI) mass spectrometry experiment, parent ions often fragment into daughter ions that give information about the parent's molecular structure. In the EI mass spectrum below, the parent mass peak at $m/z = 99$ corresponds to a radical cation ($\text{M}^{\bullet+}$) that fragments into ions with mass 84 and 59. In the boxes below, draw the structures of these ions. *You do not need to do electron pushing to answer this question—just draw the cations.* On all ion structures, make sure to specifically illustrate where the formal charge lies.



These fragments make sense in terms of the first of the two parent ions above:



In each pair, only the cation is observed in the mass spectrum.

Rubric for part (d):

PARENT:

Structure need not be correct to receive points in this problem.

3 points for any molecule that (i) has formula C_5H_9NO and (ii) has a lone-pair electron on oxygen or chlorine removed (leaving a radical cation).

DAUGHTERS:

Structures need not be correct to receive points in this problem.

3 points for correct answer.

-or-

3 points for any fragments that are substructures of answer to (b), that have the right mass, and that are drawn as cations.

-2 points for omitting positive charge.