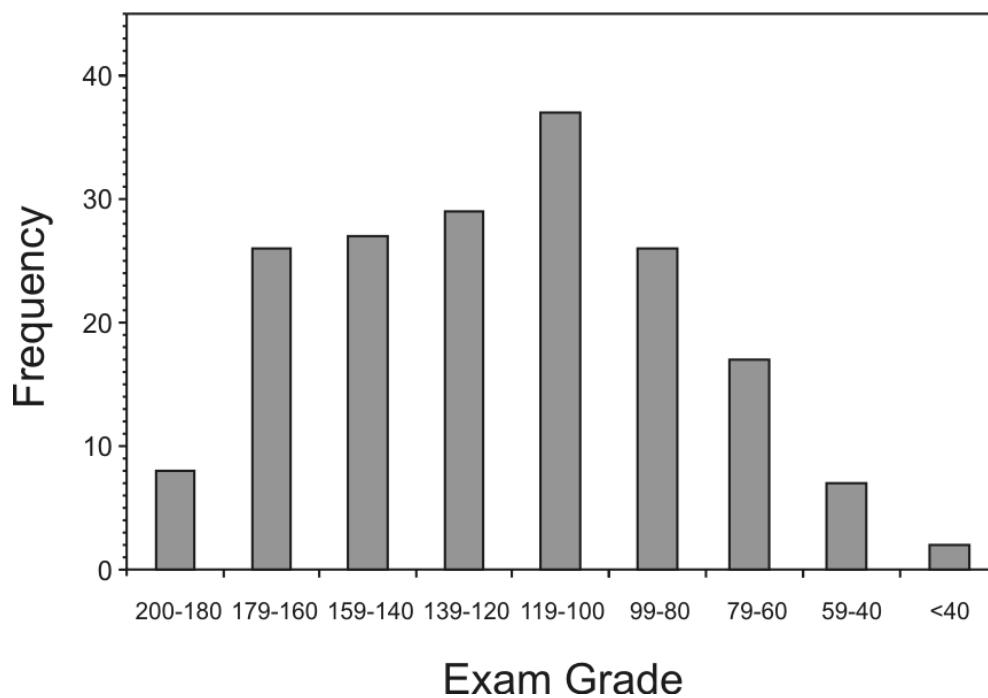


**Final Exam
Answer Key**

Final Exam Mean: 121
Final Exam Median: 120
Final Exam St. Dev.: 37

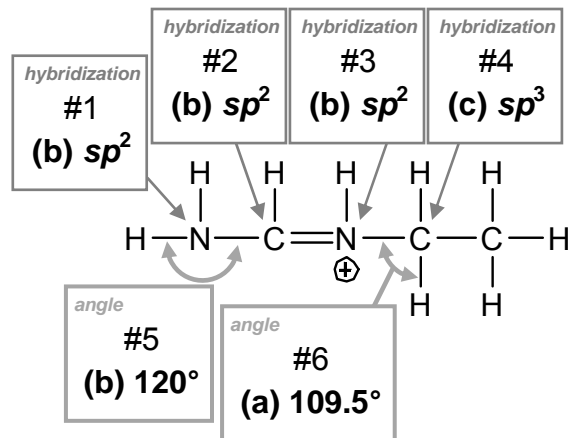


Multiple-Choice Problems

Please answer these problems on the bubble sheet.

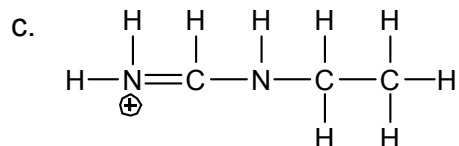
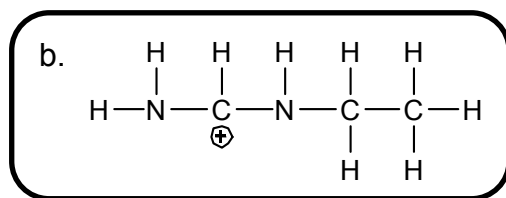
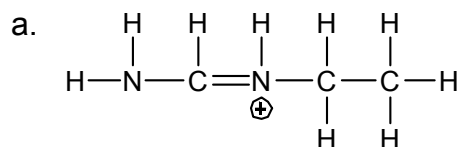
(2 pts each) For ethylformamidinium cation, drawn at right:

- For each atom marked “hybridization”, indicate whether the atom is hybridized (a) sp , (b) sp^2 , (c) sp^3 , or (d) none of these.
- For each bond angle marked “angle”, indicate whether the angle is closest to (a) 109.5° , (b) 120° , or (c) 180° .



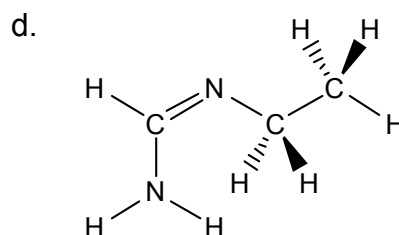
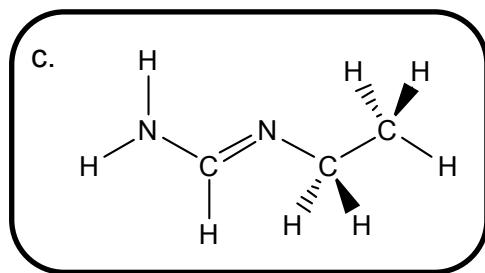
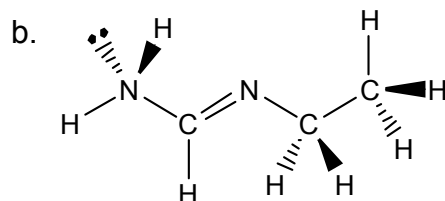
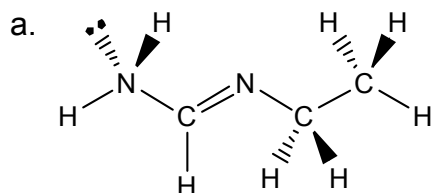
Although the nitrogen atom on the left end might look like it should be sp^3 at first glance (with its three σ bonds and one lone pair), its hybridization lowers to sp^2 , because the nitrogen has a lone pair and is adjacent to a multiple bond.

7. (3 pts) Of the resonance structures on the right, which contributes **least** to the overall electronics in ethylformamidinium cation?



All of these are valid resonance structures. Structures A and C have more bonds than structure B, and they have filled octets where B does not. Admittedly, structures A and C have a positive charge at a more electronegative atom, but Wade's list of priorities in making resonance structures says that this isn't as important as bonds or octets. So B is minor, and A and C are major.

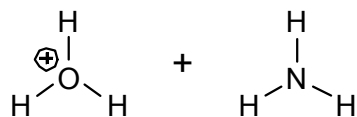
8. (3 pts) Which of the structures below represents the most stable 3-dimensional conformation of ethylformamidinium cation?



(2 pts each) Does the proton-transfer equilibrium for each acid-base pair shown below favor products, or starting materials? (Is the acid strong enough to protonate the base?)

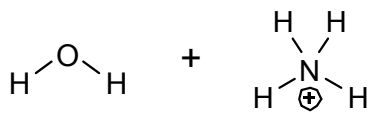
Does the equilibrium favor:

9.



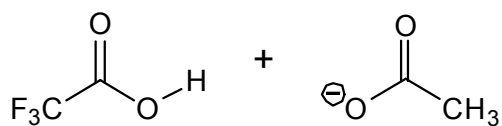
conjugate acid-base products

a. products, or
b. starting materials?



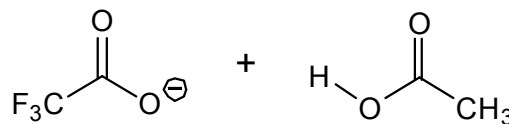
Both the starting material side and the product side have a cation--which side accommodates the charge better? Nitrogen is less electronegative than oxygen, so it tolerates the charge better, favoring the product side.

10.



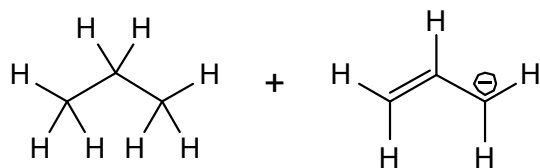
conjugate
acid-base
products

a. products, or
b. starting
materials?



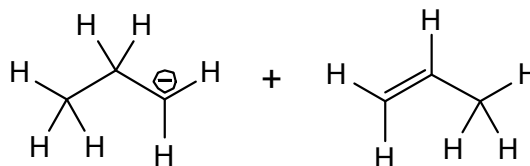
Again, both the starting material side and the product side have an ion. Both ions are stabilized by resonance, but the trifluoroacetate anion on the product side is also stabilized by induction from the electronegative fluorine atoms. So the equilibrium favors the product.

11.



conjugate
acid-base
products

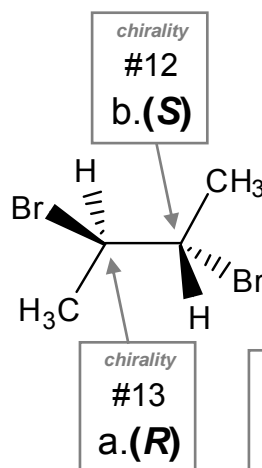
a. products, or
b. starting
materials?



Both anions are primary carbanions, but the starting material cation is stabilized by resonance. This equilibrium favors that cation.

(2 pts each) For each of the molecules drawn on the right:

- For each atom marked "chirality", indicate whether the atom would be labeled as (a) an (*R*)-chiral center, (b) an (*S*)-chiral center, or (c) not a chiral center, according to the Cahn-Ingold-Prelog classification system.
- Indicate whether the molecule would be chiral or achiral.

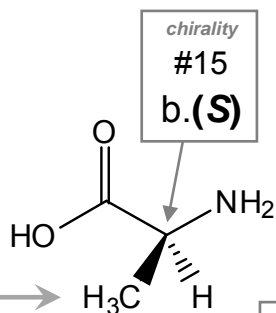


14. Is this molecule
a. chiral, or
b. achiral?

This molecule has two stereocenters with opposite Cahn-Ingold-Prelog assignments, and exactly the same groups attached. That means the molecule is *meso*, and **achiral**.

17. (2 pts) Are the methyl-group hydrogens in the structure on the right

- a. enantiotopic,
 b. diastereotopic, or
 c. neither of the above?



16. Is this molecule

- a. chiral, or
 b. achiral?

All molecules that have only one stereocenter—like this one—are chiral.

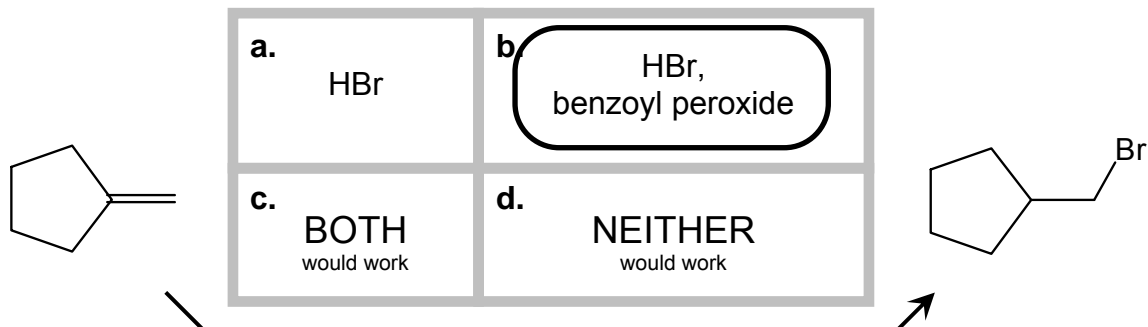
Two atoms are enantiotopic if replacing each one with a different atom—say, atom “X”—would create two new enantiomers, usually by creating a new chiral center where there wasn’t one before. That wouldn’t be true for any of the methyl group protons; replacing any of them with “X” doesn’t create a new chiral center, and so the protons aren’t enantiotopic.

Two atoms are diastereotopic if replacing them creates two diastereomers instead of two enantiomers, again usually by creating a new chiral center. Once again, that isn’t what happens here.

So the answer was “neither of the above”.

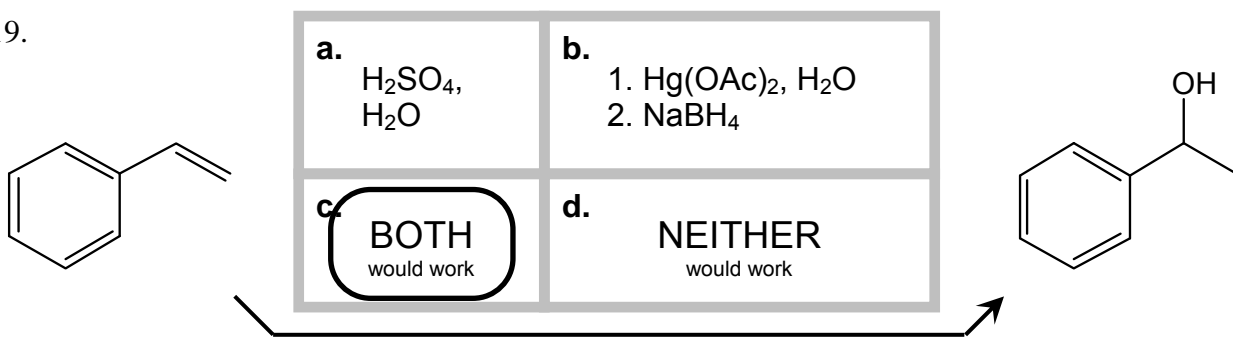
(4 pts each) Each of the reactions below is drawn with two possible reaction conditions. If only one of the two reaction conditions would generate the given molecule as the major product, answer with the corresponding letter. If both sets of conditions would accomplish the reaction, answer (c) “BOTH”. If neither set of reaction conditions would succeed, answer (d) “NEITHER”.

18.



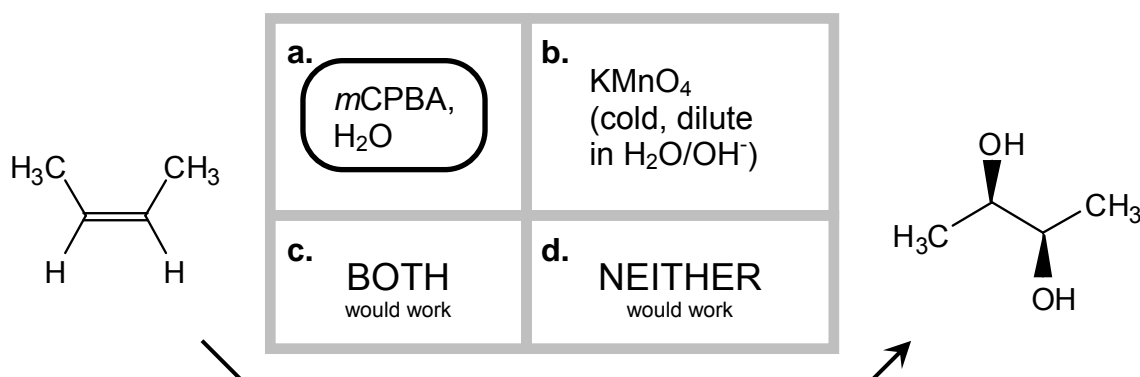
HBr adds to alkenes with Markovnikov orientation (with Br at the more substituted position), unless peroxide is added, in which case the HBr adds anti-Markovnikov. Here, the product is anti-Markovnikov.

19.

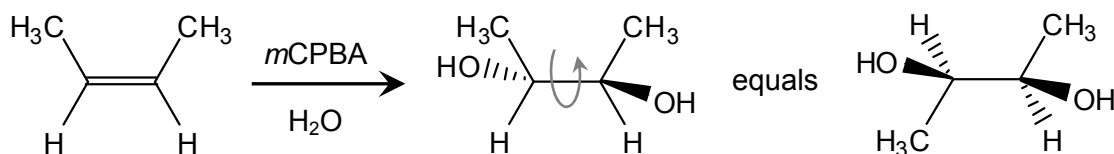


Both of these sets of reagents add H-OH Markovnikov to the double bond. The first set is not as clean as the second, but they both work.

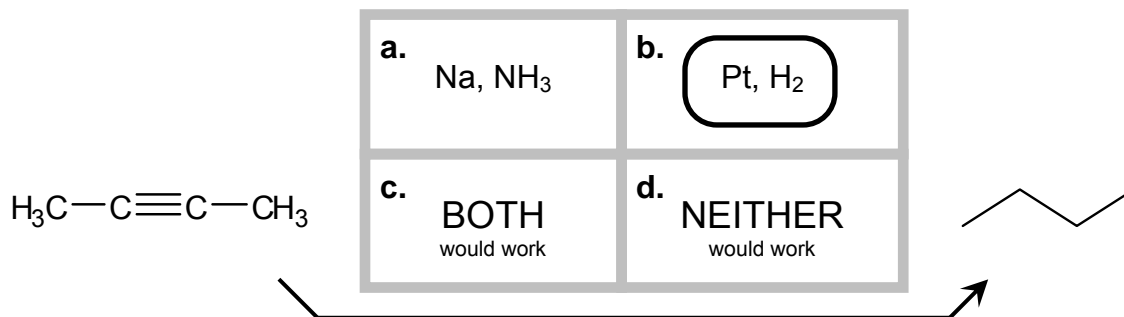
20.



Both of these sets of reagents perform dihydroxylation—they add an –OH group to either side of an alkene. They differ in that *m*CPBA performs *anti*-dihydroxylation (adding the two –OH groups to opposite faces of the alkene), while KMnO₄ performs *syn*-dihydroxylation (adding the two –OH groups to the same face of the alkene). Here, even though the product is drawn to make it look like the –OH groups are on the same side, they are on opposite sides of the starting material:

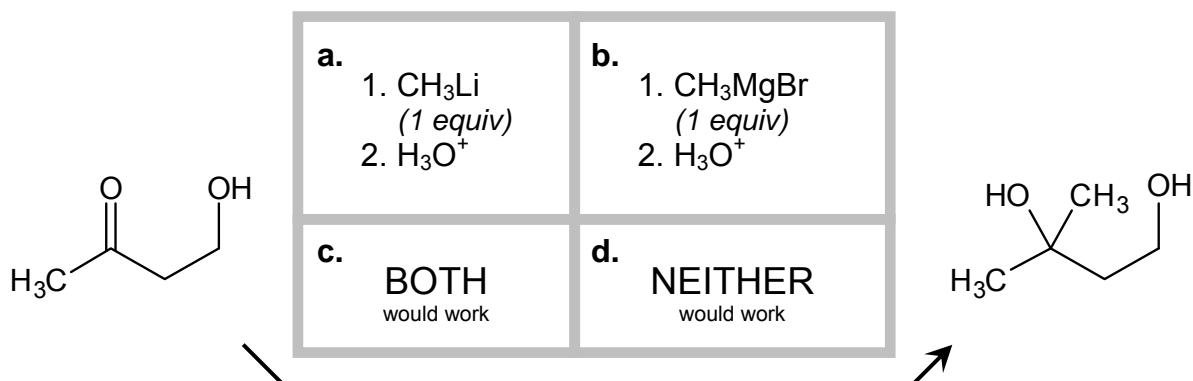


21.

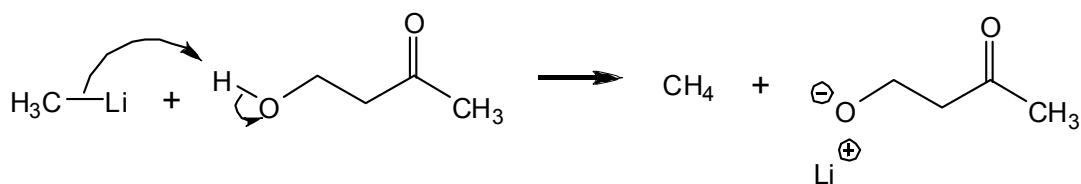


Both of these sets of reagents add H₂ to alkynes. Na/NH₃ adds only one molecule of H₂ to yield a *trans*-alkene as a product. Pt/H₂, on the other hand, exhaustively hydrogenates the alkyne all the way to an alkane.

22.

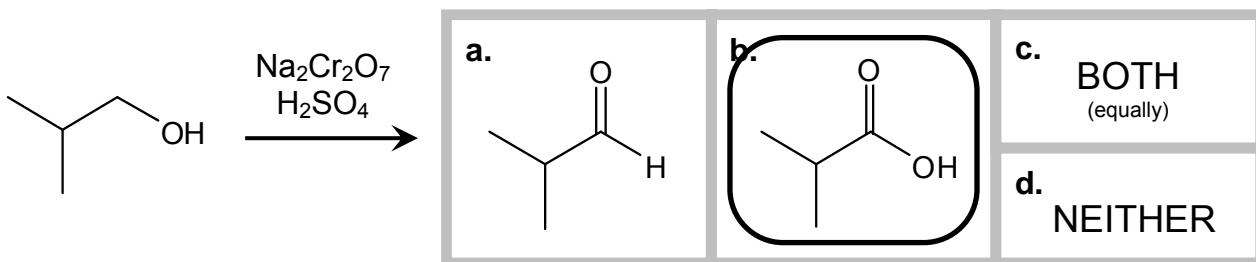


Although both alkyllithium (R-Li) and Grignard (R-MgX) reagents will add to carbonyl groups, they are also extremely basic. In the presence of even a weak acid, such as an alcohol, either one will be protonated before it has a chance to react with the carbonyl:



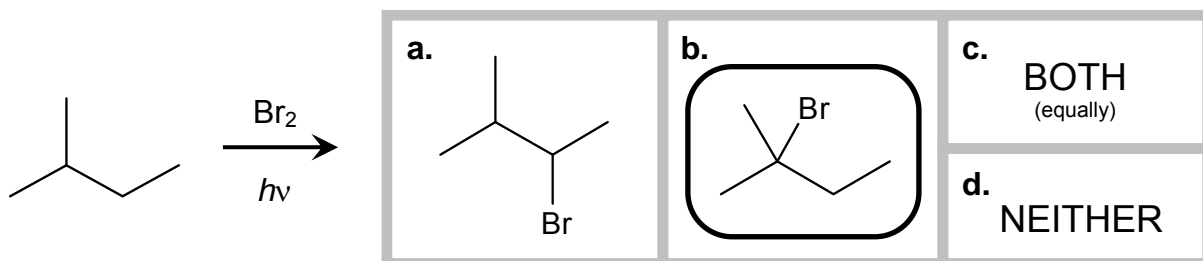
(4 pts each) Each of the reactions below is drawn with two possible products, marked (a) and (b). If one of the two products predominates, answer with the letter corresponding to the correct product. If the two products are produced equally, answer (c) BOTH. If neither product would result from the reaction, answer (d) NEITHER.

23.



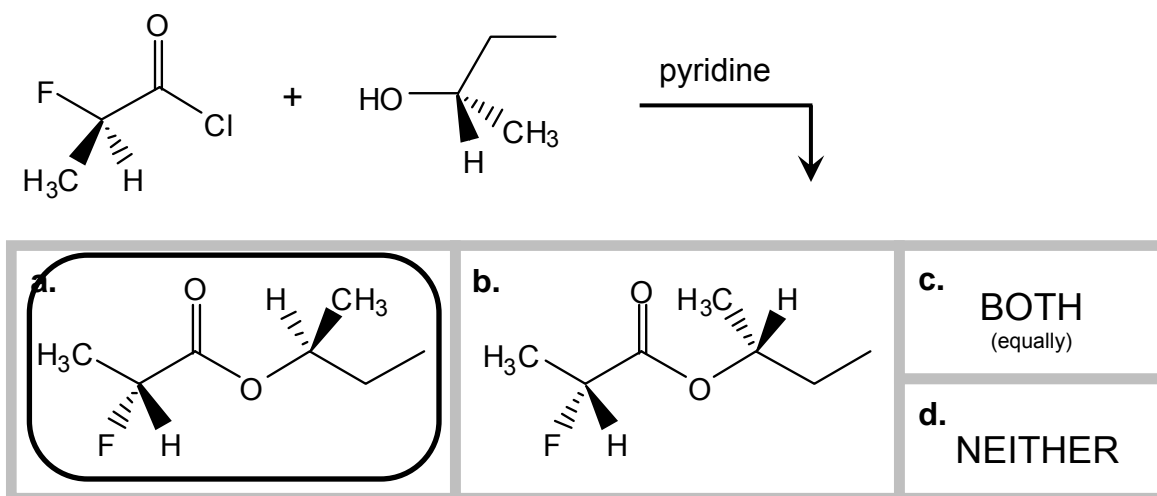
Chromate is a strong oxidizing agent, and will oxidize the primary alcohol all the way to the carboxylic acid.

24.



Radical bromination replaces an H with a bromine atom at the most substituted position (via the most stable radical intermediate).

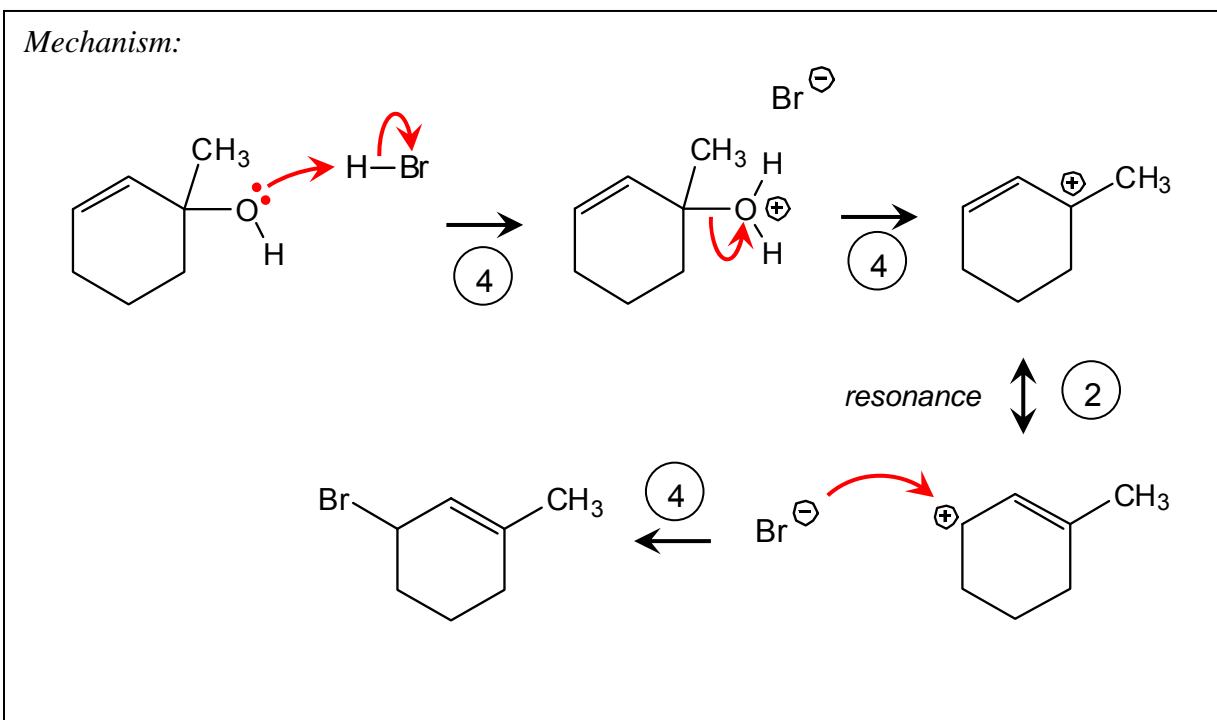
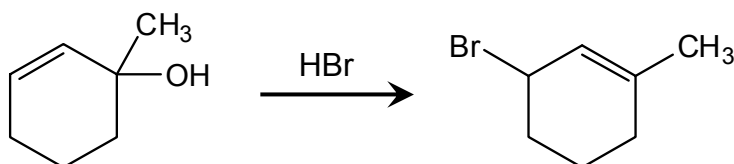
25.



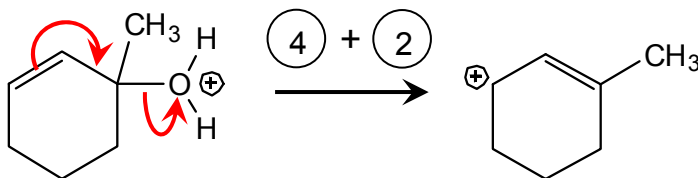
Combination of an acyl chloride with an alcohol to form an ester doesn't change the stereochemistry in either starting material.

32. (29 pts) For the reactions shown below, draw a mechanism that explains how the product is generated from the starting material. In your answer, make sure that you:

- Draw each step of the mechanism separately;
- Use “electron pushing” to show where the electrons in each step go;
- Use only the molecules that you are given; do not invoke reactants or solvents that aren't in the problem.



Resonance is not a mechanistic step per se—it's just two ways of drawing the same molecule. As a result, you did not need to push electrons to show resonance, or even draw multiple resonance structures explicitly. You can integrate resonance into a mechanistic step; for instance, you could have combined it with the departure of H₂O:



As long as resonance is in your answer somewhere—either integrated into a step, or drawn explicitly—you get 2 points.

OH^- is a terrible leaving group. If you drew the first step as OH^- leaving, you only got 4 points for that step (out of 8 for the combined first two steps).

Rubric: (14 points total this part)

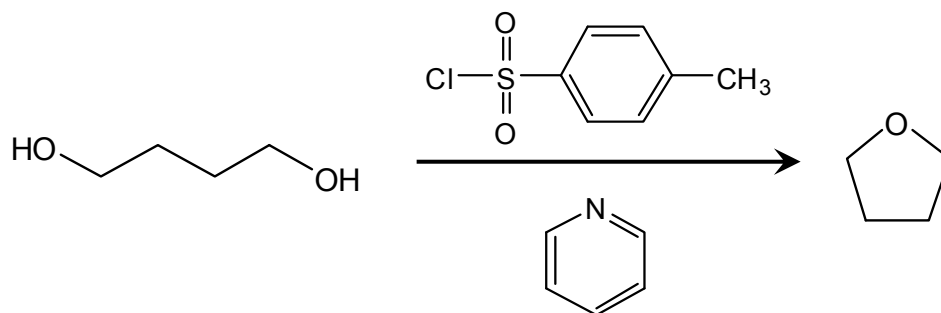
Overall notes:

Things that have left (e.g., Br^-) and spectators may be omitted until they are needed.

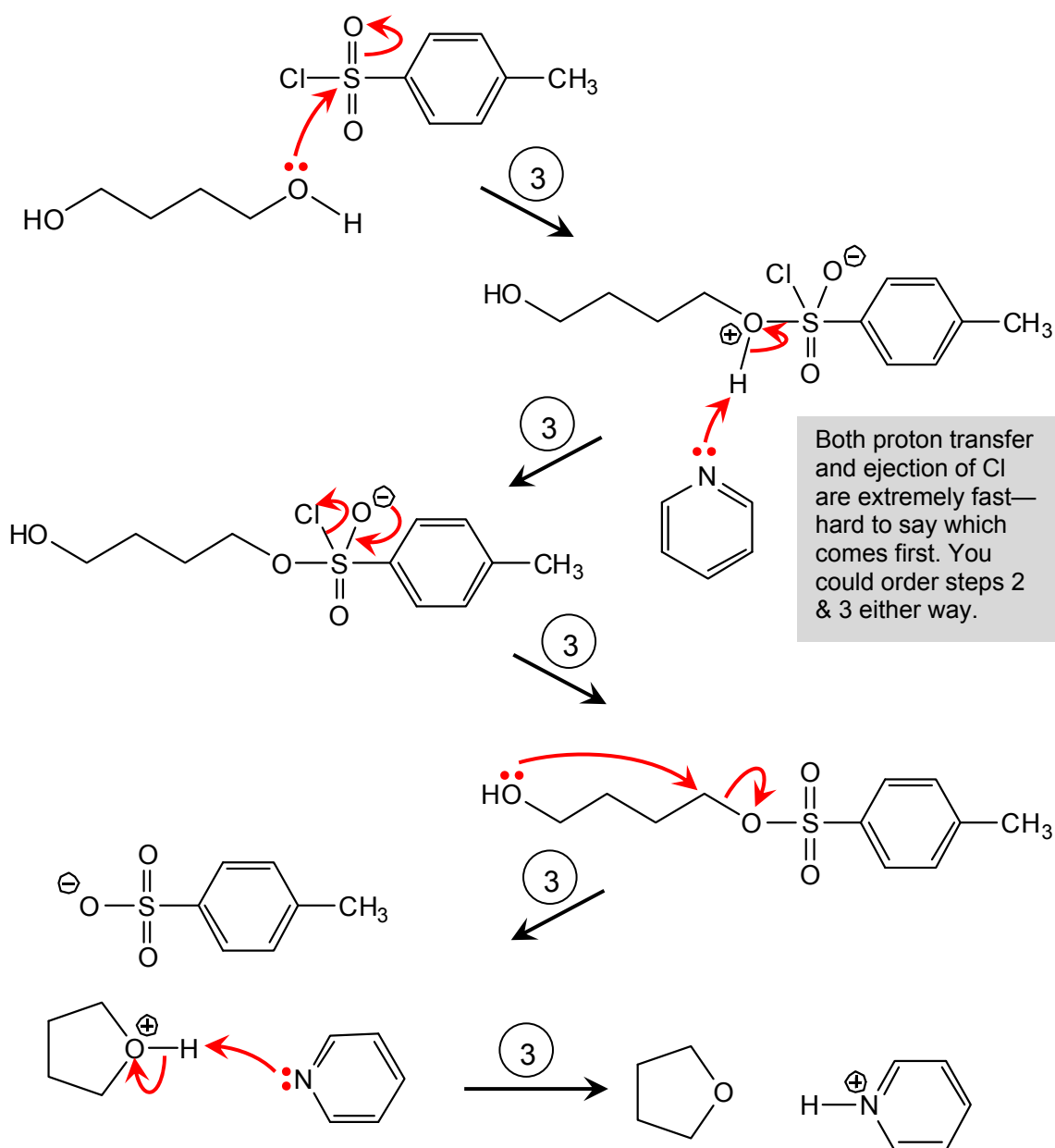
-2 points, for each arrow in each step, for errors in drawing arrows. Arrow must start at an electron pair, and end at nucleus where electrons will newly interact. Can only lose points if you get them.

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

-2 points for each step combined with another, EXCEPT resonance. Combining resonance with another step is just fine.

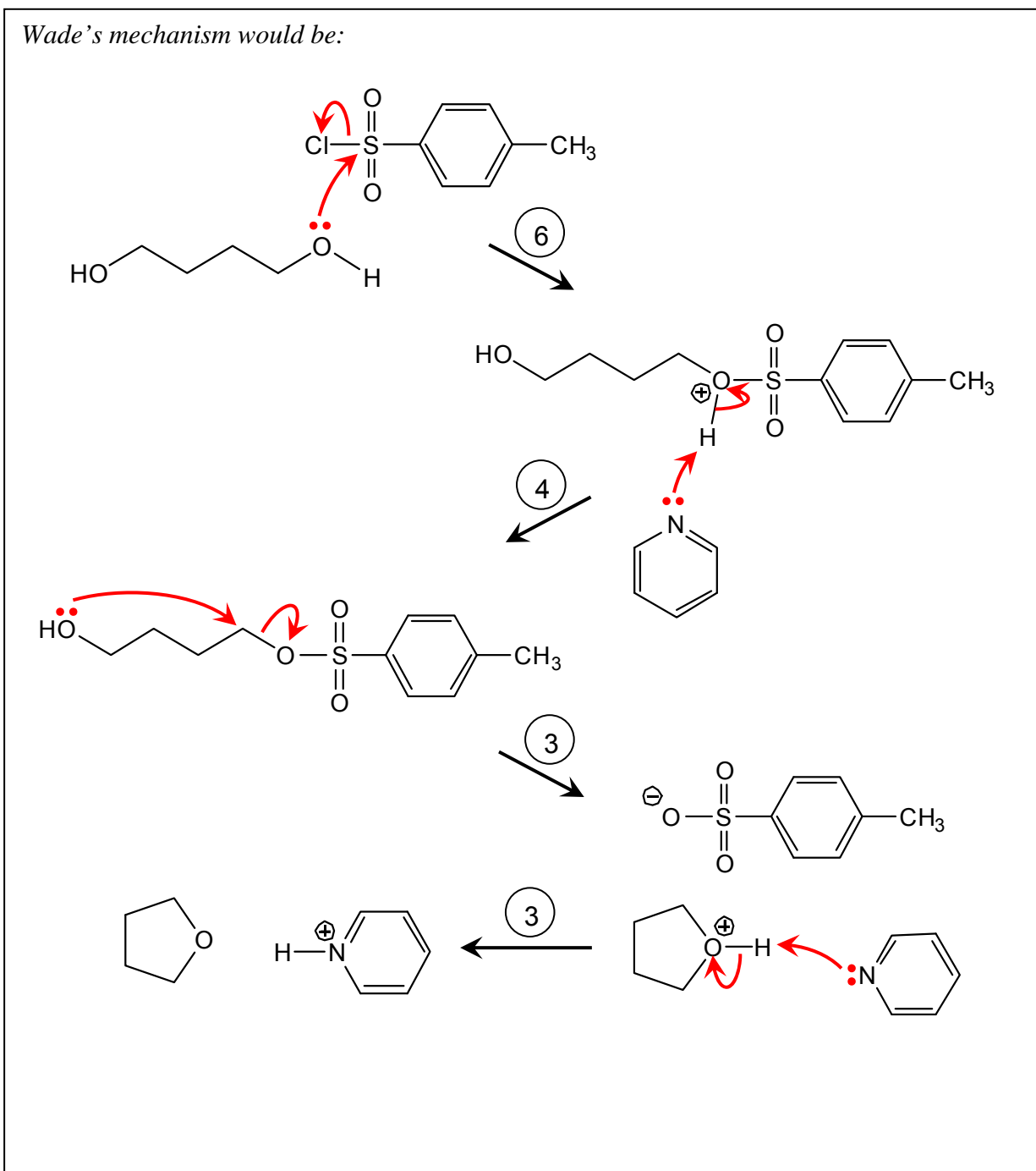


My mechanism would be:



The mechanism I've drawn invokes a five-coordinate sulfur atom as an intermediate in the initial nucleophilic addition to TsCl. This is analogous to the tetrahedral carbon intermediate that is observed when a nucleophile adds to a carbonyl C=O. Researchers have observed the tetrahedral intermediate in C=O additions directly, but not yet the S=O adduct; nevertheless, chemists usually infer the five-coordinate adduct based on C=O chemistry.

But not Wade. Wade shows a different mechanism for tosylation of an alcohol on page 470 of the text that does not involve a five-coordinate sulfur at the center--in other words, that has the initial oxygen nucleophile directly displace chloride.



I think Wade is probably wrong, but he's not definitively wrong, and so we accepted either mechanism here.

Rubric: (15 points total this part)

Overall notes:

Things that have left (e.g., Cl) and spectators may be omitted until they are needed.

-2 points, for each arrow in each step, for errors in drawing arrows. Arrow must start at an electron pair, and end at nucleus where electrons will newly interact. Can only lose points if you get them.

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

-2 points for each step combined with another.

6 points total for substitution of chloride in TsCl by alcohol oxygen.

This must occur before deprotonation by pyridine; pyridine is not a strong enough base to deprotonate an alcohol to any significant extent. However, we did not take off these 6 points if you deprotonated first.

Substitution can be two-step (with addition to sulfonyl, followed by ejection of Cl) or concerted.

3 points for first deprotonation by pyridine.

This must occur after attack on TsCl. (See note above about order of events.) No partial credit for this step if out of order.

2 points partial for deprotonation with base other than pyridine (e.g. TsO⁻, Cl).

3 points for intramolecular attack by other alcohol on tosylate.

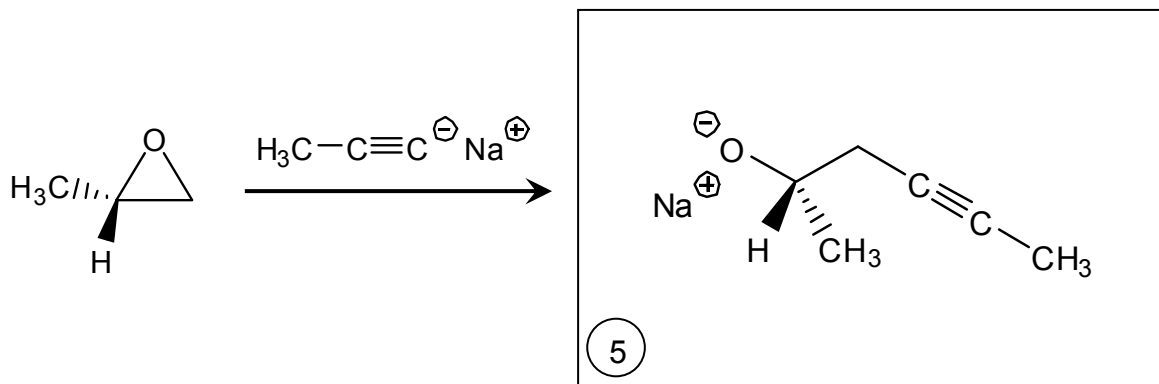
Again, this must occur before deprotonation by pyridine, but you still get these points if you put things out of order. (It's the next ones you lose.)

3 points for second deprotonation by pyridine.

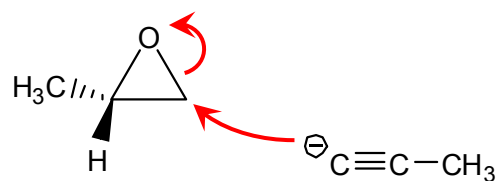
This must occur after attack by oxygen. See note above about order of events. No partial credit for this step if out of order.

2 points partial for deprotonation with base other than pyridine (e.g. TsO⁻, Cl).

33. (25 pts) Draw the missing reactant or product in the empty boxes. For products, give the predominant, most favored product. Illustrate stereochemistry in your answer where appropriate. For reactions that yield multiple enantiomers, draw only one enantiomer in the box, and include the note "+ enantiomer".

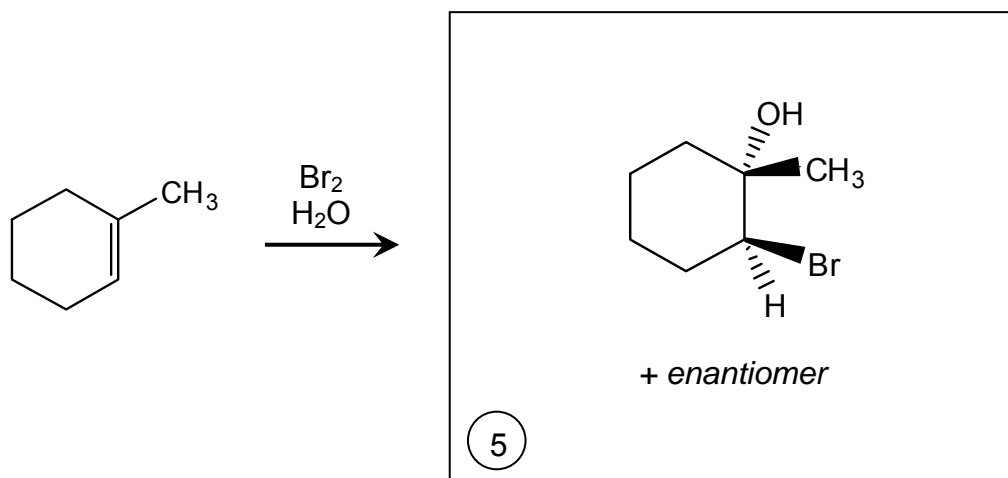


The acetylide anion adds to the epoxide at the less hindered carbon.

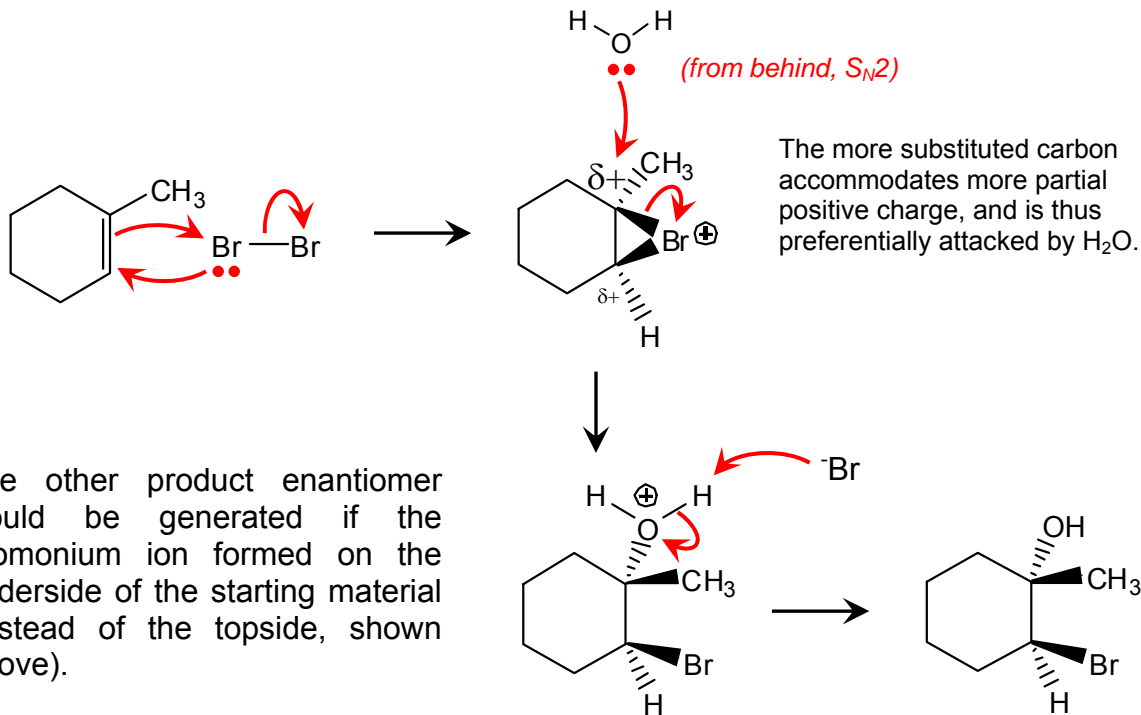


Rubric:
5 points.

Full credit for omitting Na^+ , or for protonating oxygen. (No proton source was provided in the problem, but no points were taken off if you assumed one.)
-2 points for each trivial structural mistake (omitting a carbon, charge, etc.)
-2 points for omitting or incorrectly drawing stereochemistry in (any) product.
3 points partial for adduct at more substituted carbon of epoxide.



Here, formation of a bromonium ion is followed by addition of water to the more substituted carbon:



The other product enantiomer would be generated if the bromonium ion formed on the underside of the starting material (instead of the topside, shown above).

Rubric for this part:

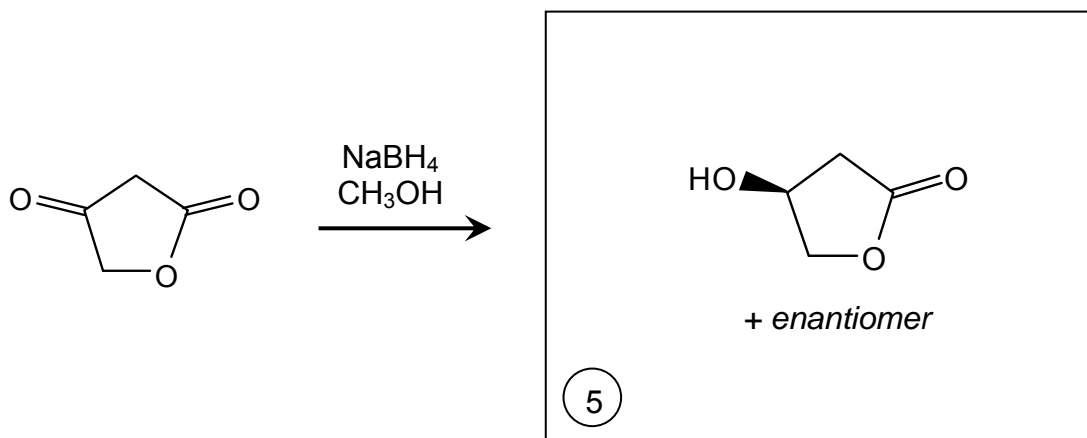
5 points.

4 points partial for not writing "+ enantiomer".

3 points partial for incorrect stereochemistry (syn adduct), indeterminate stereochemistry (no wedges/dashes), or incorrect regiochemistry (Br at more substituted carbon).

2 points partial for dibromide (any stereochemistry).

-2 points for each trivial structural mistake (omitting a carbon, charge, etc.)



NaBH₄ is a mild reducing agent. It is strong enough to reduce ketones to alcohols, but not esters. As a result, only the ketone is reduced.

Rubric for this part:

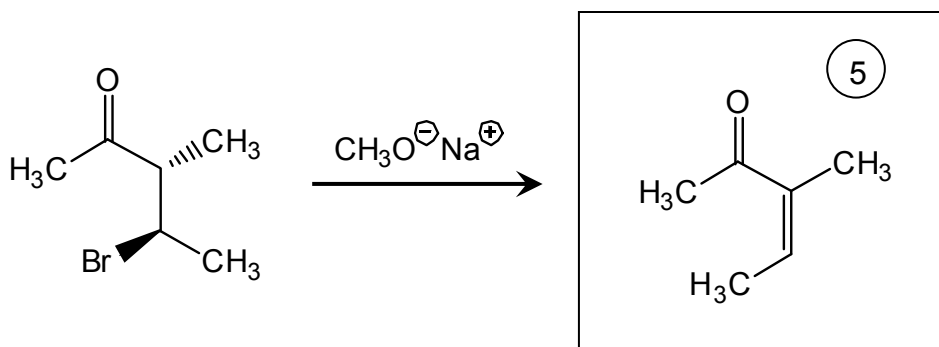
5 points.

No need to show stereochemistry in your answer, or to write “+ enantiomer”.

(Product is racemic, true, but drawing bond as a line would imply this.)

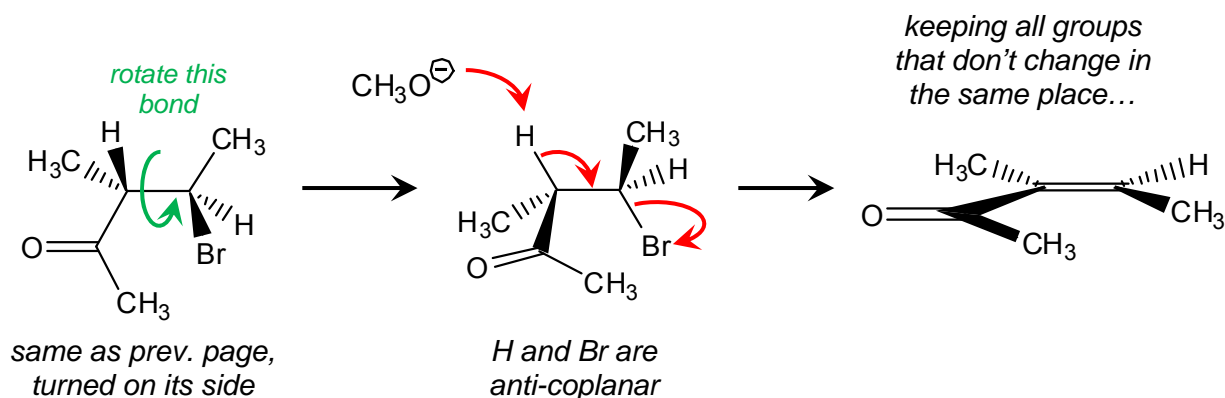
3 points partial for reducing ester (to anything) in addition to or instead of ketone.

-2 points for each trivial structural mistake (omitting a carbon, charge, etc.)



In general, sodium methoxide is a strong base, and a better base than it is a nucleophile, so it will react with the bromide via E2 if it can. There are two H's on carbons adjacent to (α to) the leaving group—the methyl hydrogen, and the single H next to the carbonyl (C=O bond). The α-carbonyl H would give the more substituted (and resonance-stabilized) alkene product, so we'll focus on it.

E2 requires anti-coplanar arrangement of the H being taken and the leaving group. The way the molecule is drawn, the H and Br are not on opposite sides of the C-C bond that connects them, so that bond will need to rotate to put them in position:



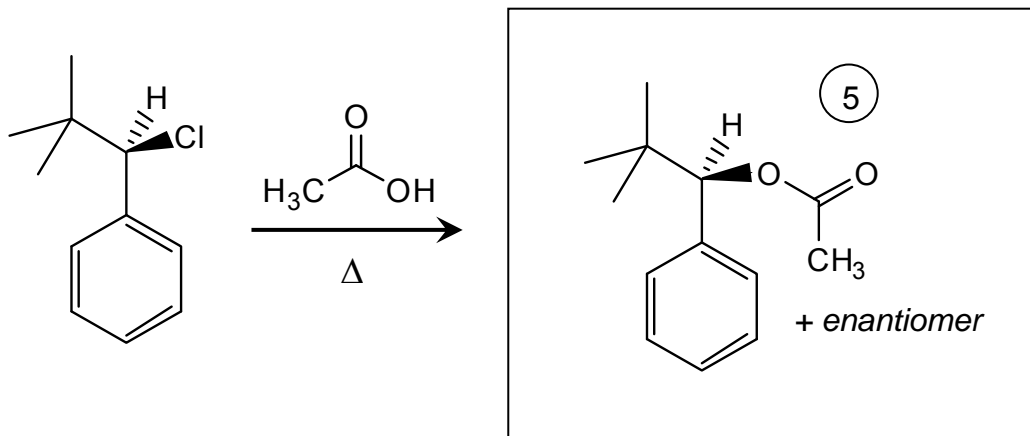
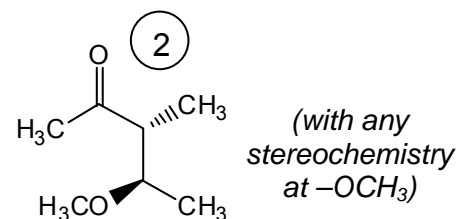
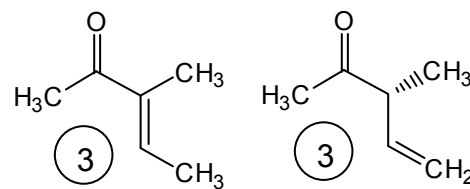
Rubric for this part:

5 points for correct structure.

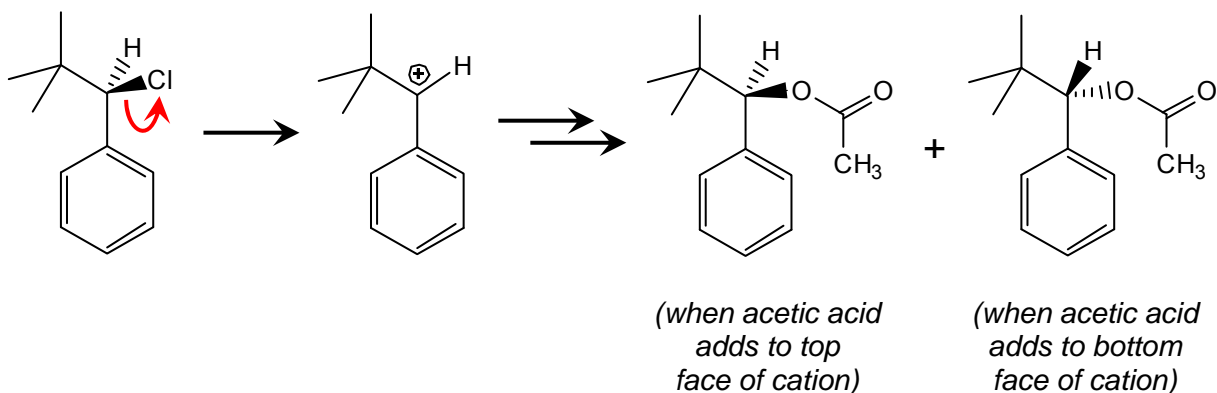
3 points partial for bromine elimination product with wrong or unclear stereochemistry or wrong regiochemistry.

2 points partial for any bromine substitution product.

-2 points for each clearly trivial structure mistake. The answer that you intend needs to be clear for you to get these points.



Acetic acid is a poor nucleophile, and the added heat tips us off that this should be an S_N1 or $E1$ reaction. There are no protons α to the Cl leaving group, so it cannot be $E1$; this must be S_N1 . S_N1 passes through an achiral carbocation intermediate, which reacts to generate a racemic mixture of products:



Rubric for this part:

5 points for correct structure and either (a) including "+ enantiomer" or (b) not illustrating stereochemistry (which infers racemate).

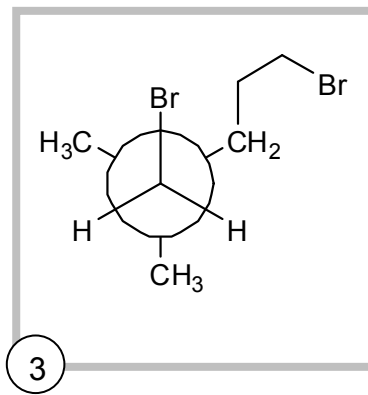
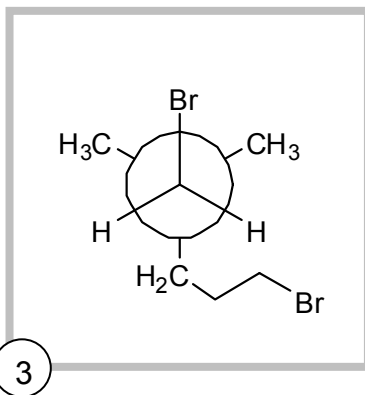
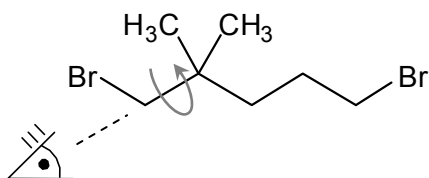
4 points partial for omitting "+ enantiomer" from correct answer that shows correct enantiomer only.

3 points partial for inversion of stereochemistry only (as if reaction were S_N2).

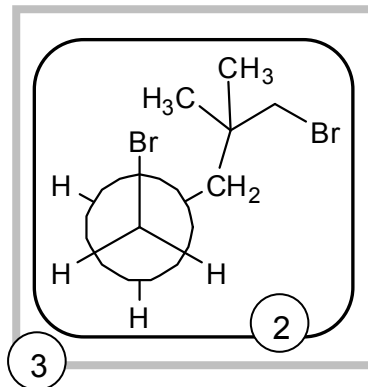
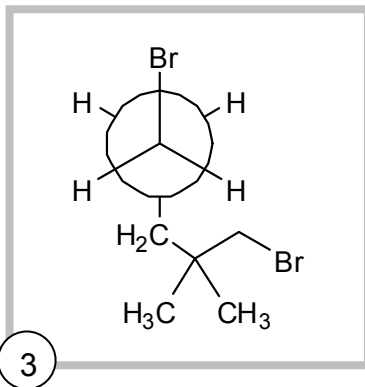
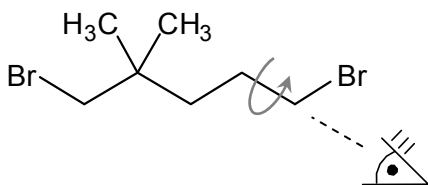
-2 points for each clearly trivial structure mistake.

34. (32 pts)

(a)



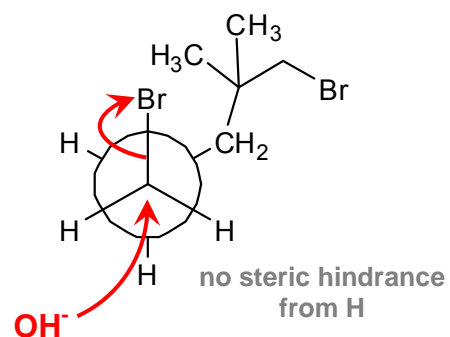
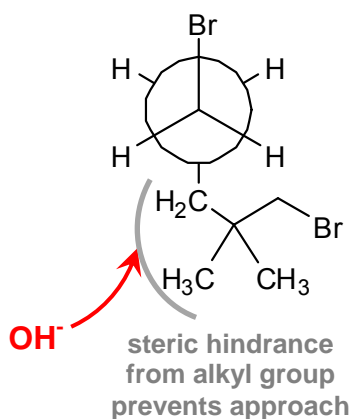
(or, could draw mirror image of this one; any two of these three receives full credit)

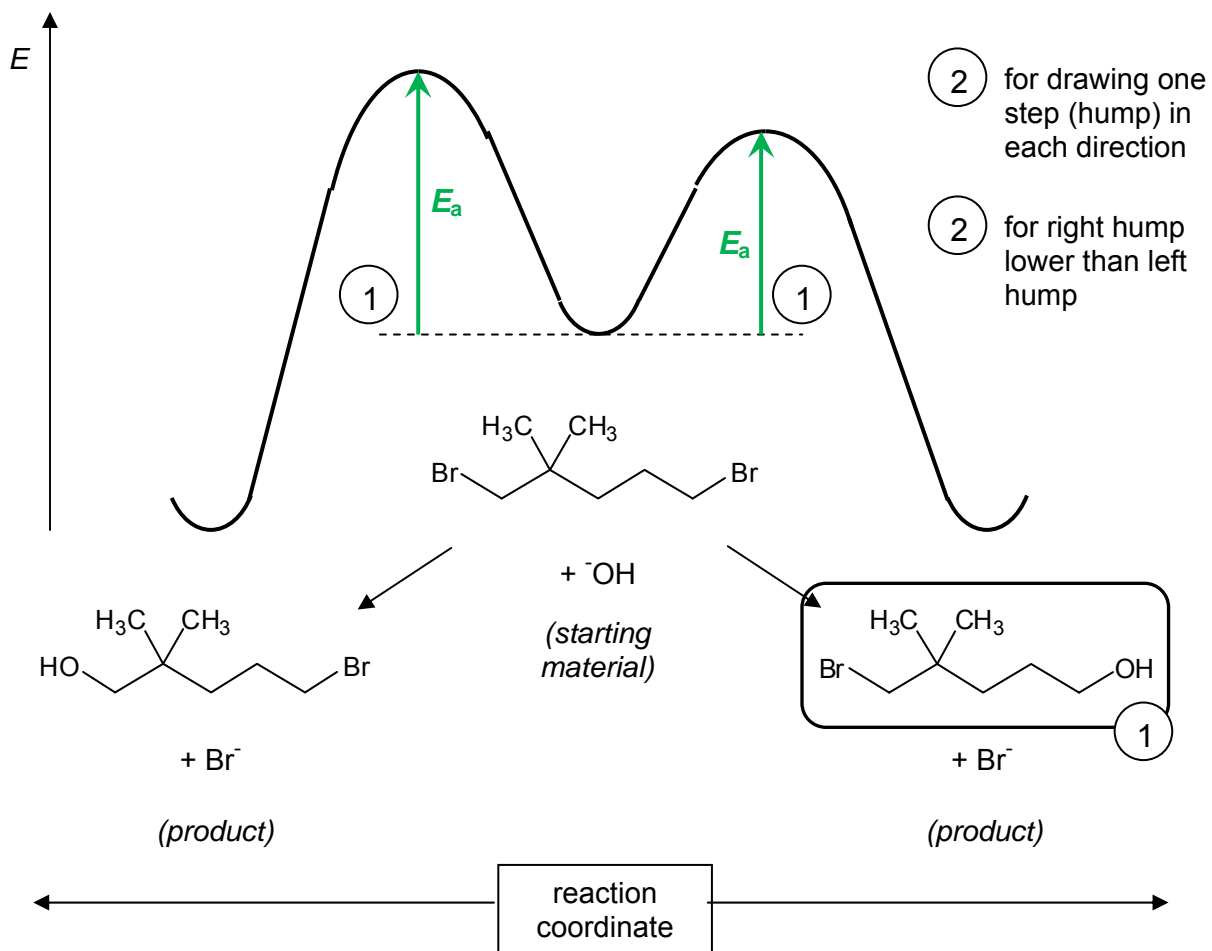
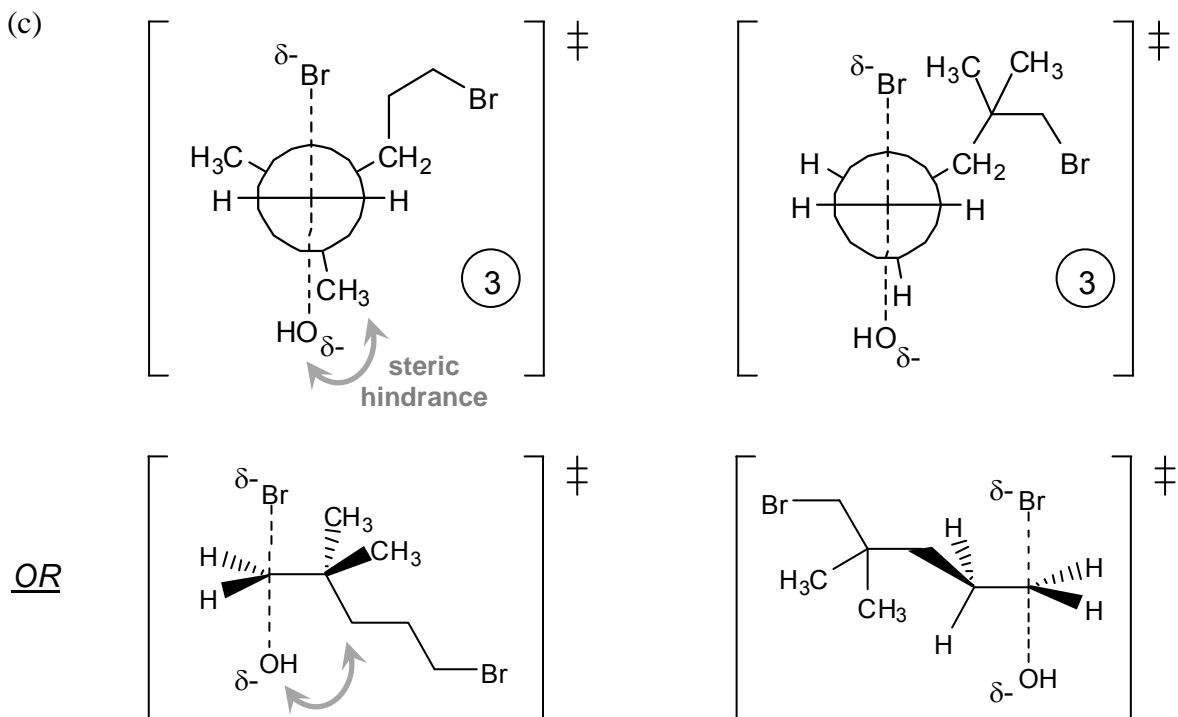


(again, could draw mirror image of this one; any two of these three receives full credit)

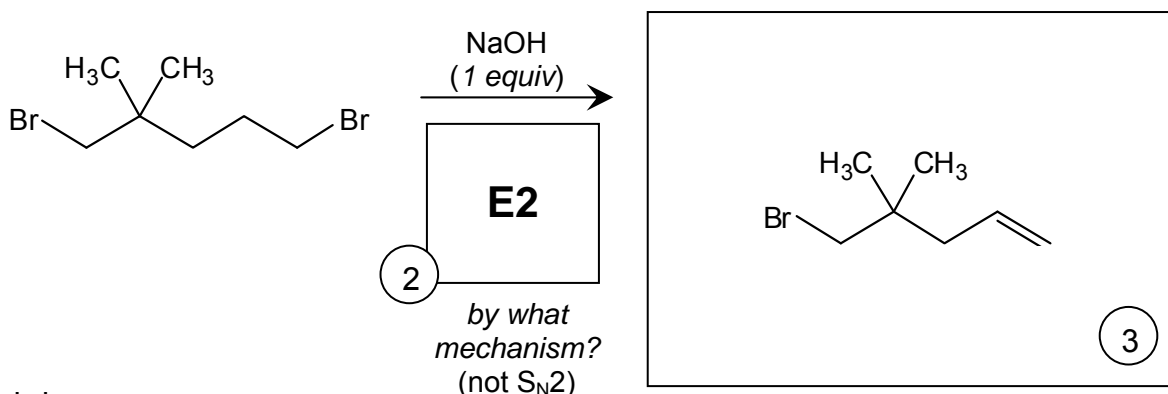
(b) Of the four Newman projections you drew above, which would react the fastest with OH^- in an $\text{S}_{\text{N}}2$ reaction? **Circle one Newman projection.**

Sure, the anti-conformer is the most stable. But, the conformation with the least amount of steric hindrance opposite the leaving group—with the most room for OH^- to approach—will react the fastest. So:





(d) In fact, both of these S_N2 products are *minor* products of the reaction between one equivalent of OH^- and the starting material, because OH^- is a stronger base than it is a nucleophile. What molecule would be the preferred product of this reaction, and by what mechanism would it be produced?



Rubric:

for parts (a/b): (14 points)

3 points for each staggered Newman projection.

I have drawn one anti and one gauche, but could also draw two gauche. Any two will do.

-1 point for each trivial structural mistake.

1 point partial on each rotamer if you omitted rest of chain (& just drew atoms on the rotated bond)

2 points for circling any conformer where $-\text{Br}$ is *anti* to an $-\text{H}$.

for part (c): (13 points)

3 points for each transition state structure:

Any conformation is acceptable.

1 point for backside attack by OH^- on Br ;

1 point for partial bonds;

1 point for partial charges.

-2 points if transition state doesn't correspond to product (say, if TS for left reaction was also drawn for right reaction), or if there is no clear difference between the two TS structures. Only lose these points if you get them.

6 points for potential energy diagram:

2 points for drawing each process as a single (S_N2) step;

2 points for drawing unhindered transition state as lower in energy than neopentyl TS;

1 point for labeling E_a on each curve. (Curve does not have to be correct, and relative heights can be wrong.)

1 point for circling right-hand product.

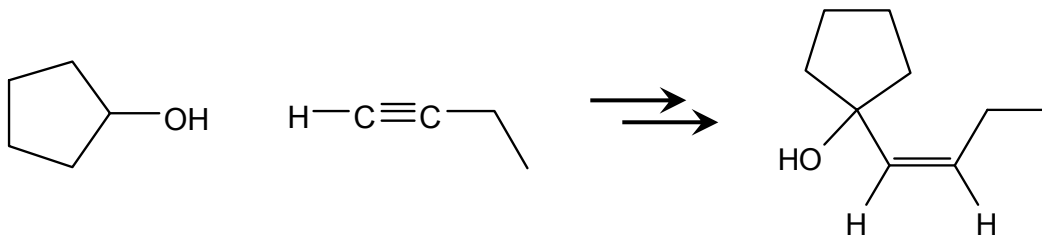
for part (d): (5 points)

3 points for correct product.

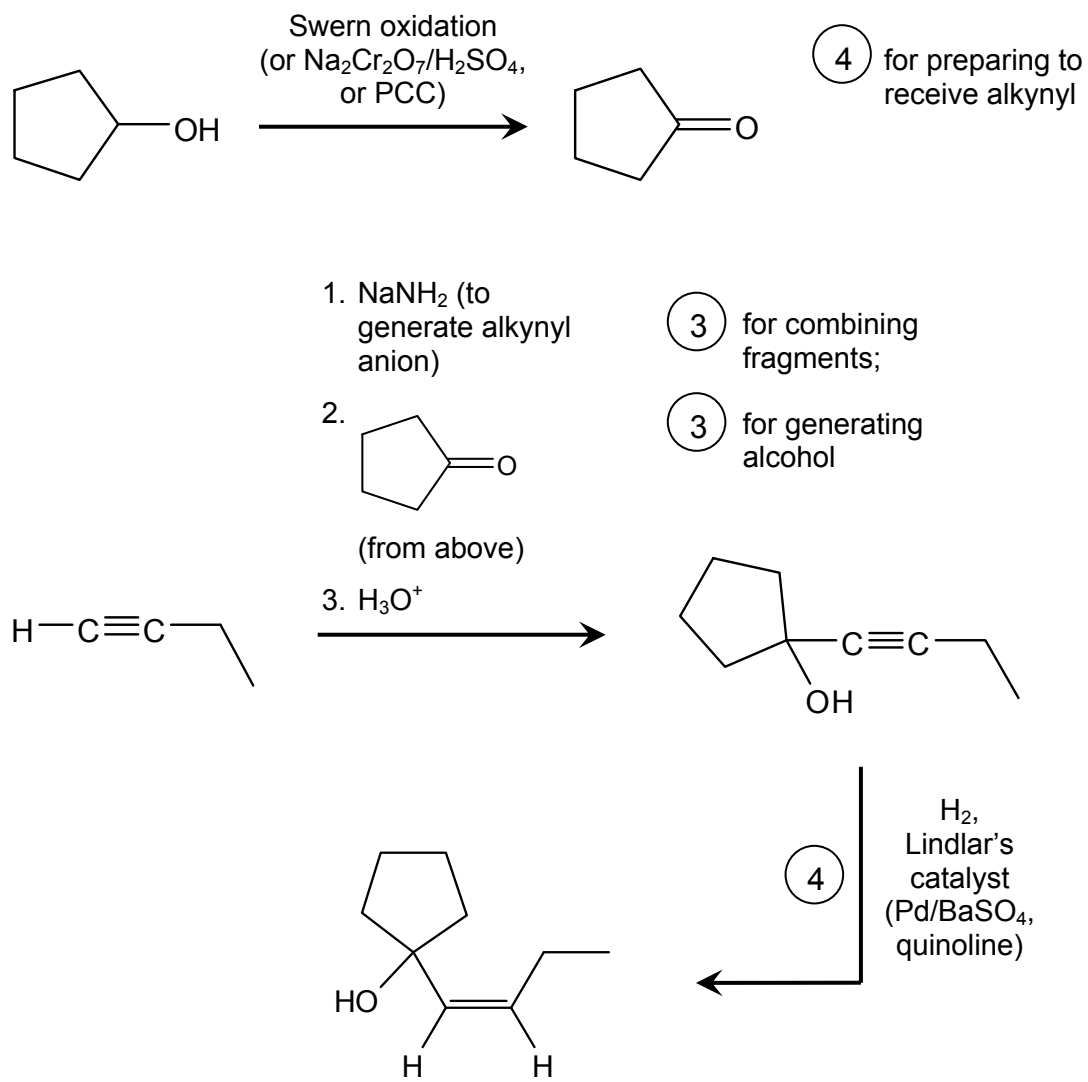
1 point partial for any alkene.

2 points for "E2".

9. (14 pts) For the starting materials and product 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.



One possible route:



Rubric:

The synthesis requires four tasks: (a) getting cyclopentanol ready to react with the alkyne; (b) making the alkyne reactive (probably as an alkynyl anion), and combining it with the cyclopentyl fragment; (c) creating the alcohol group in the product (which could happen as a result of a and b, or could be done separately; and (d) hydrogenating the alkyne to generate an alkene.

-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. (Especially relevant to hydrogenation step.)

-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.

Making cyclopentanol reactive towards alkyne (a): 4 points.

Lots of potential ways to do this. Some end up becoming alcohol in product, some do not. Examples that would be worth full credit:

- Oxidation to ketone w/ Swern/chromate/PCC;
- Tosylation (TsCl/pyridine);
- Conversion to halide (SOCl₂, PBr₃, P/I₂; 3 points partial for HX).

Deprotonating alkyne, and combining alkynylsodium with electrophile (b): 3 points.

1 points partial for deprotonation alone. There is no need to show alkynyl anion itself; just "NaNH₂" is enough.

Other 2 points awarded if alkynyl anion is combined with something—anything that works—to form a C-C bond. So, combining alkynyl with ketone, tosylate, halide, or epoxide—no matter whether points were awarded in part (a) or not—receive credit here.

1 point partial of 3 above if combination would not work, but could if it were engineered correctly.

H₃O⁺ workup can be omitted (though, in real life, it couldn't be).

Full credit for drawing parts 1-3 of this recipe as explicit steps, or combining them onto the same arrow with numbers as I have. However, if you combine them on the same arrow, you must have numbers; you can't add all the reagents at the same time.

Generating alcohol group (c): 3 points.

If answer used alkynyl + ketone, alcohol is generated automatically. 3 points for this.

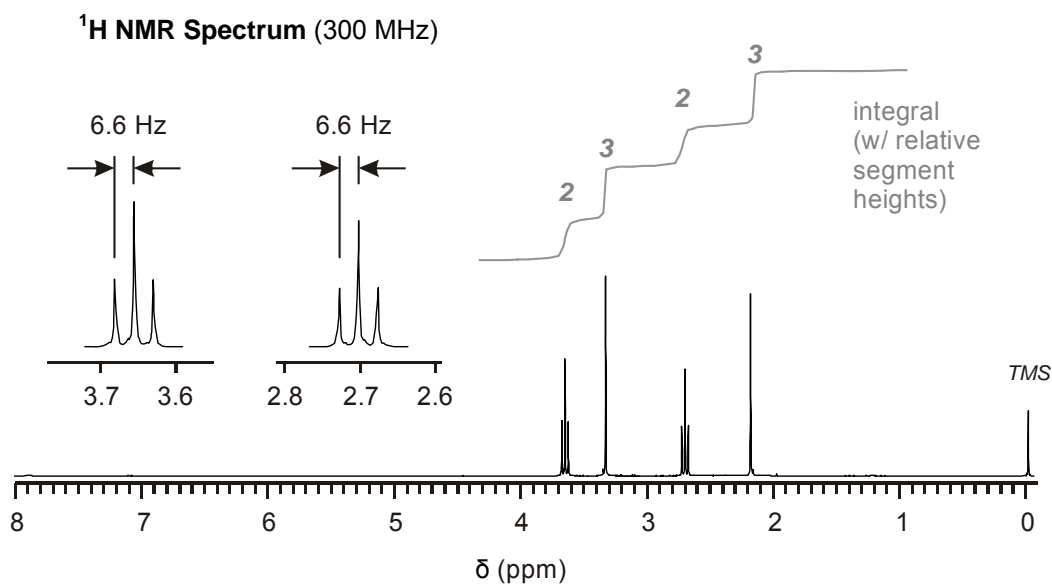
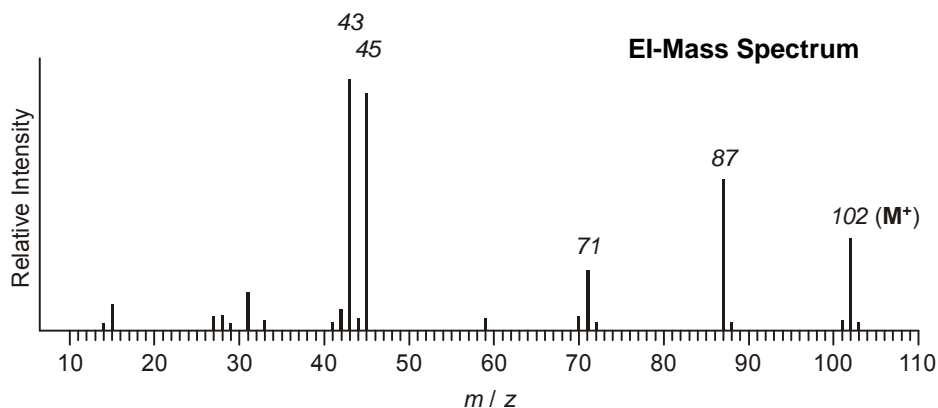
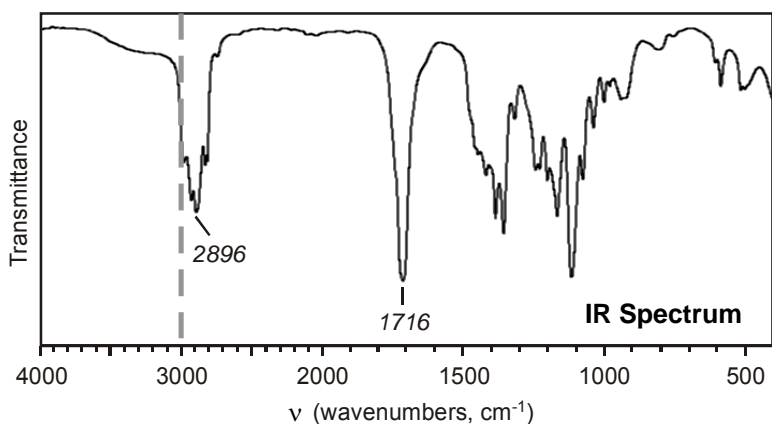
If answer used alkynyl + cyclopentyl-LG, allylic halogenation (with NBS) followed by S_N2 with hydroxide is worth 1 point. The S_N2 would not be clean, lots of E2.

Hydrogenation to cis-alkene (d): 4 points.

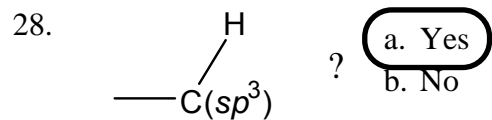
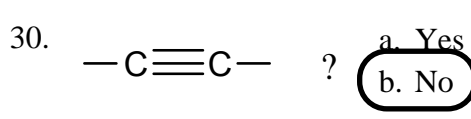
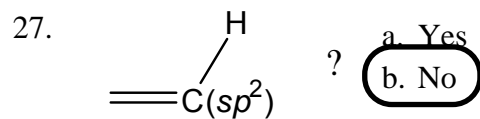
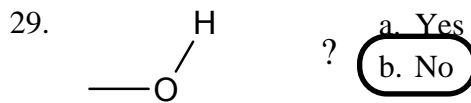
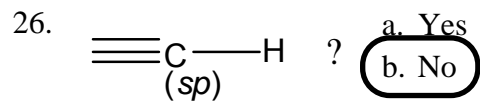
2 points partial for alternative hydrogenation protocol (Na/NH₃, or Pt/H₂).

2 points partial if you do this too early (before there are two substituents to be cis).

The spectra on this page correspond to a pure molecule, isolated from a chemical reaction. High-resolution mass spectrometry determined an exact mass of 102.0681 amu for the highest-mass (parent, M^+) peak in the MS spectrum, which corresponds to a molecular formula of $C_5H_{10}O_2$.



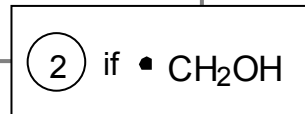
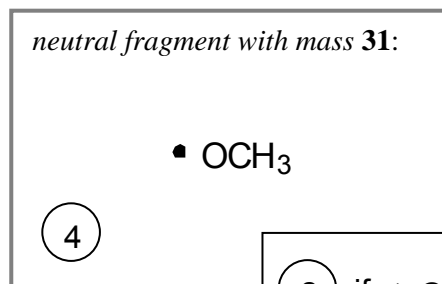
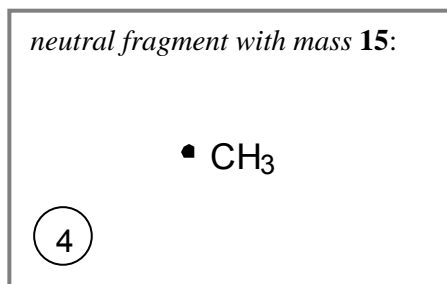
(1 pt each) Based on the features in the IR spectrum, which of the following functional groups would you expect the unknown molecule to have? Would the molecule contain a



The IR spectrum really has only two features above 1500 cm^{-1} —a peak at 1716 cm^{-1} , and a C-H peak below 3000 cm^{-1} . The C-H peak has to be $\text{C}(sp^3)\text{-H}$ only; $\text{C}(sp^2)\text{-H}$ and $\text{C}(sp)\text{-H}$ would both be found above 3000 cm^{-1} . The IR resonance chart says that the peak at 1716 cm^{-1} is a C=O bond. (Sadly, problem #31 was supposed to ask you whether a C=O was present, but I copied and pasted the list from a different test, and didn't replace the last item. Needless to say, a molecule that has no nitrogen atoms in it cannot have a C≡N group in it.)

36. (26 pts)

- (a) The mass spectrum shows a parent mass peak at $m/z = 102$, and two fairly high-mass fragment ions at $m/z = 87$ and $m/z = 71$. For these fragment ions to be observed, the parent molecule must have ejected neutral (invisible) fragments with mass $(102 - 87) = 15$ and $(102 - 71) = 31$ atomic mass units (amu). What do you think are the structures of these neutral fragments?



There is only one fragment formula, given the C, H, and O atoms we have to work with in the parent, that adds to mass 15: CH_3 -. So, our molecule must have a methyl group. There are two possible fragment structures with mass 31; we

ruled out the presence of an alcohol in problem 29, so the fragment must be $\text{CH}_3\text{O}-$. (We gave partial credit for the alcohol fragment HOCH_2- .)

- (b) The mass spectrum shows a small peak at $m/z = 103$, *above* the mass of the parent M^+ peak (102). Assuming that the material is pure (i.e., that there are no higher-mass contaminants in the sample), how is it possible that the mass of some molecules would be higher than expected? *Please be brief. You could probably answer this in 10 words or less.*

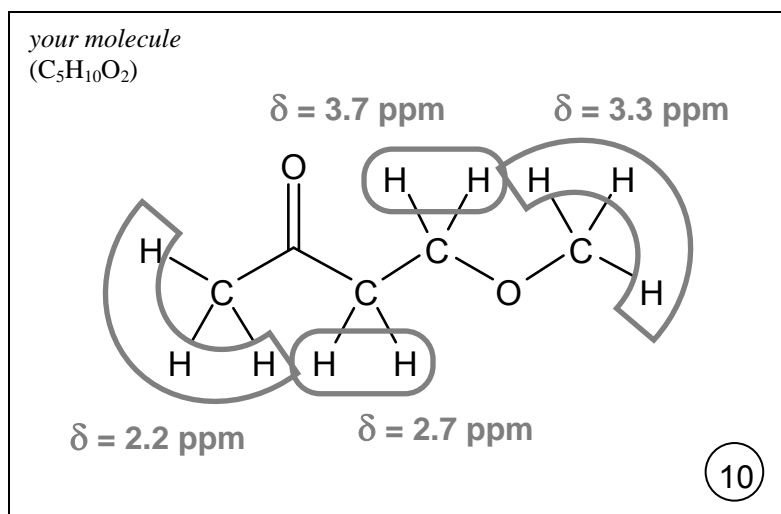
Any molecule that has one heavy isotope in it—say, where one of the carbons is a ^{13}C instead of a ^{12}C (probability: 1 out of every 100 carbons), or one of the hydrogens is an ^2H instead of an ^1H (probability: 1 out of every 10,000 hydrogens)—will show up in the mass spectrum as one a.m.u. higher than the “parent” peak. For this molecule, with 5 carbons, the intensity of the $m/z = 103$ peak should be $\sim 5\%$ that of the $m/z = 102$ peak.

4

Rubric for part (b):

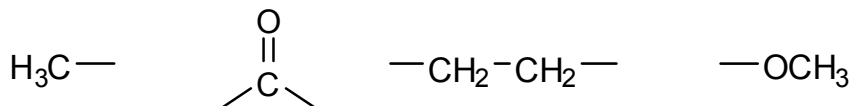
4 points for any answer that references a heavy isotope (or the words “heavy isotope”).

- (c) **What is the structure of the molecule?** In the box below, draw your molecule’s structure again, including all hydrogens. Then circle each set of equivalent H’s, and label each with its unique ^1H NMR chemical shift.



The ^1H NMR has many useful clues in it. Out of the four resonances, two are multiplets—indicating H’s with neighbors, and presumably with each other as neighbors—and two are singlets with intensity three, each indicating three

equivalent protons with no neighbors. We can already guess that one of those singlets is from the $-\text{OCH}_3$ group we predicted in part (b), and the other singlet is probably another $-\text{CH}_3$ group somewhere. Each of the other two resonances represents two H's with two neighboring H's (because each multiplet is a triplet). So that means our molecule has the following fragments:



Rubric for part (c):

2 points for correct structure.

Structure need not be correct to receive the other 8 points in this problem.

2 points for each δ value. (8 points total this box.) *To get full credit, circle must include all equivalent protons for your structure, match the integration intensity of the peak, match the type of proton that would appear at that frequency, and δ value must be within ± 0.1 ppm of value shown above.*

3.7, 3.3 ppm: Must be O-C-H protons.

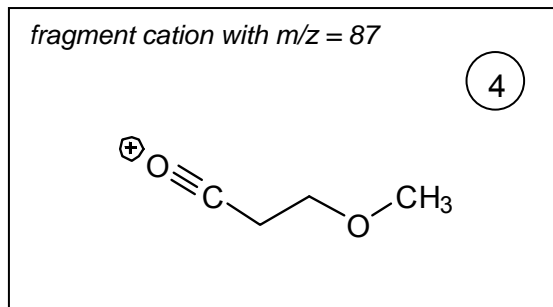
1 point partial for if chemical shift matches proton type, but integral and/or splitting do not match.

2.7, 2.2 ppm: Any proton adjacent to C=O.

1 point partial for if chemical shift matches proton type, but integral and/or splitting do not match.

1 point partial if integral and splitting match, but chemical shift would normally be for alkyl.

- (d) Given your answer above, what is the structure of the daughter (fragment) cation in the mass spectrum that has $m/z = 87$? *You do not need to do electron pushing to answer this question—just draw the cation.*



Rubric for part (d):

4 points (full credit) for any structure that (i) is a cation; (ii) has mass 87; and (iii) is related by bond cleavage to the answer written in part (c).

-2 points if any oxygen has an unfilled octet. Cleavage will prioritize putting electrons on oxygen.