

5.53 (Molecular Structure and Reactivity I) Problem Sets

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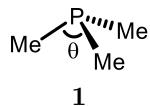
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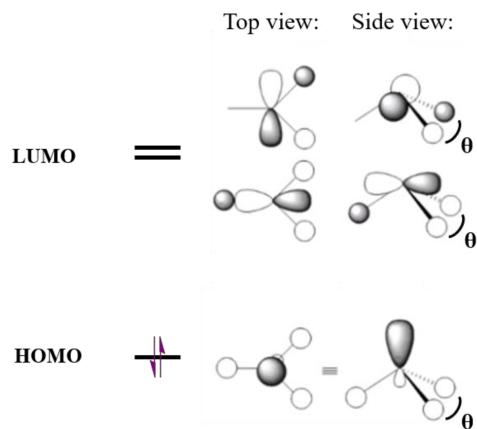
1 Applications of Molecular Orbitals

- 9/25: The questions pertain to the material we have covered from Introduction (Sep 5) to Pericyclic Reactions (Sep 19). For the molecular orbital (MO) diagrams, please draw the MOs with appropriate energy levels, fill in the electrons, and draw cartoons that illustrate the orbital interactions.

1. The geometry of PMe_3 (**1**) is known to be pyramidal.

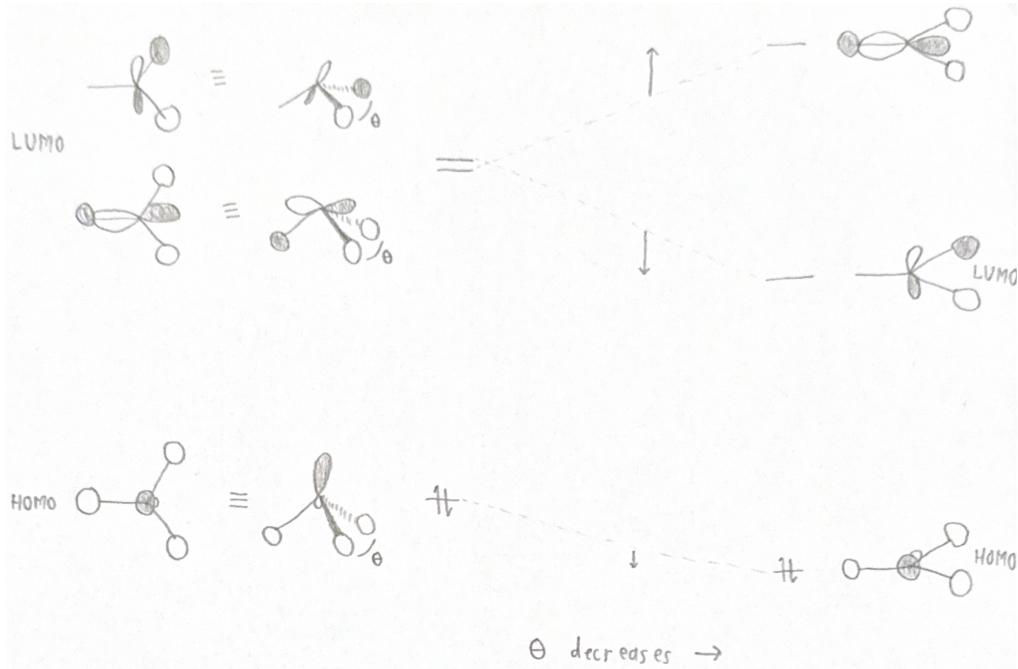


A qualitative MO diagram for the frontier orbitals of PMe_3 can be drawn as follows.



- a) How will the energies of the frontier orbitals change if we decrease one C–P–C angle, denoted as θ , by symmetrically moving the two methyl groups closer to each other? Draw a Walsh diagram for the frontier orbitals to explain. Assume that the bond lengths are unchanged.

Answer. Let's consider the energy changes orbital by orbital, from bottom to top.



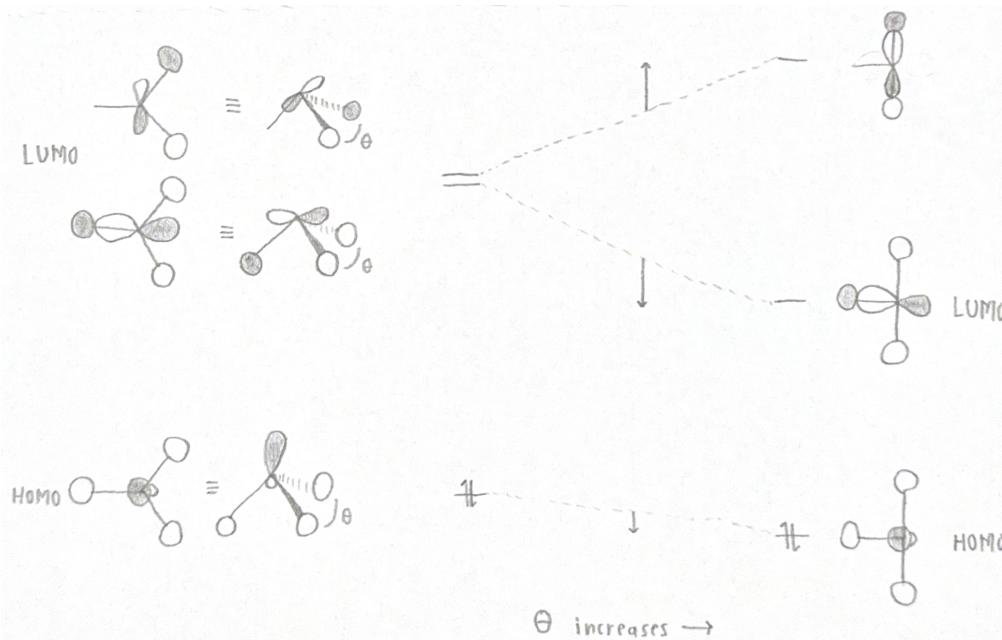
HOMO: As θ decreases with fixed bond lengths, the two methyl orbitals adjacent to θ get closer and begin to participate in a *slightly* stabilizing, secondary interaction. This will cause the HOMO to go down in energy slightly.

Bottom LUMO: As θ decreases, we will observe the same slightly stabilizing secondary interaction as in the HOMO. However, this effect will be dwarfed with increasing primary destructive interference with the phosphorous atom's shaded *p*-lobe. Thus, the energy of this orbital will go up more than the energy of the HOMO went down.

Top LUMO: As θ decreases, we'll gain some destructive secondary interference, but we'll mostly lose primary destructive interference as we approach a primary nonbonding orientation in the nodal plane of the *p*-orbital. Thus, the energy of this orbital will go down on a similar order of magnitude to how much the bottom LUMO went up. \square

- b) How will the energies of the frontier orbitals change if we instead increase θ while maintaining the bond lengths? Draw a Walsh diagram for the frontier orbitals to explain.

Answer. Similarly to part (a), we will also do this analysis orbital by orbital, from bottom to top.

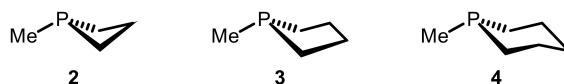


HOMO: As θ increases with fixed bond lengths, the two methyl orbitals adjacent to θ *both* get closer to the methyl on the left side of the diagram. This will induce another *slightly* stabilizing, secondary interaction, but likely a slightly bigger stabilizing interaction than the analogous one in part (a).

Bottom LUMO: Decreasing primary destructive interference between the shaded *p*-lobe and the two unshaded methyl lobes that are moving results in a net stabilizing interaction that is more significant than the slightly stabilizing interaction in the HOMO.

Top HOMO: Increasing primary destructive interference leads to a similarly significant destabilizing interaction. \square

- c) Rank the relative nucleophilicity and electrophilicity of the following molecules, and rationalize your hypotheses.



Answer. θ is unstrained in **4**, θ is slightly decreased in **3**, and θ is more decreased in **2**. Additionally, a higher energy/more destabilized HOMO will make a species more nucleophilic, and a lower energy/more stabilized LUMO will make a species more electrophilic. Thus, all we need to answer this question is the MO diagram in part (a).

Since the HOMO gets more stabilized as θ decreases,

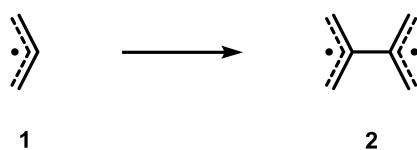
4 is the most nucleophilic, then **3**, then **2**.

Since the LUMO also gets more stabilized as θ decreases,

2 is the most electrophilic, then **3**, then **4**.

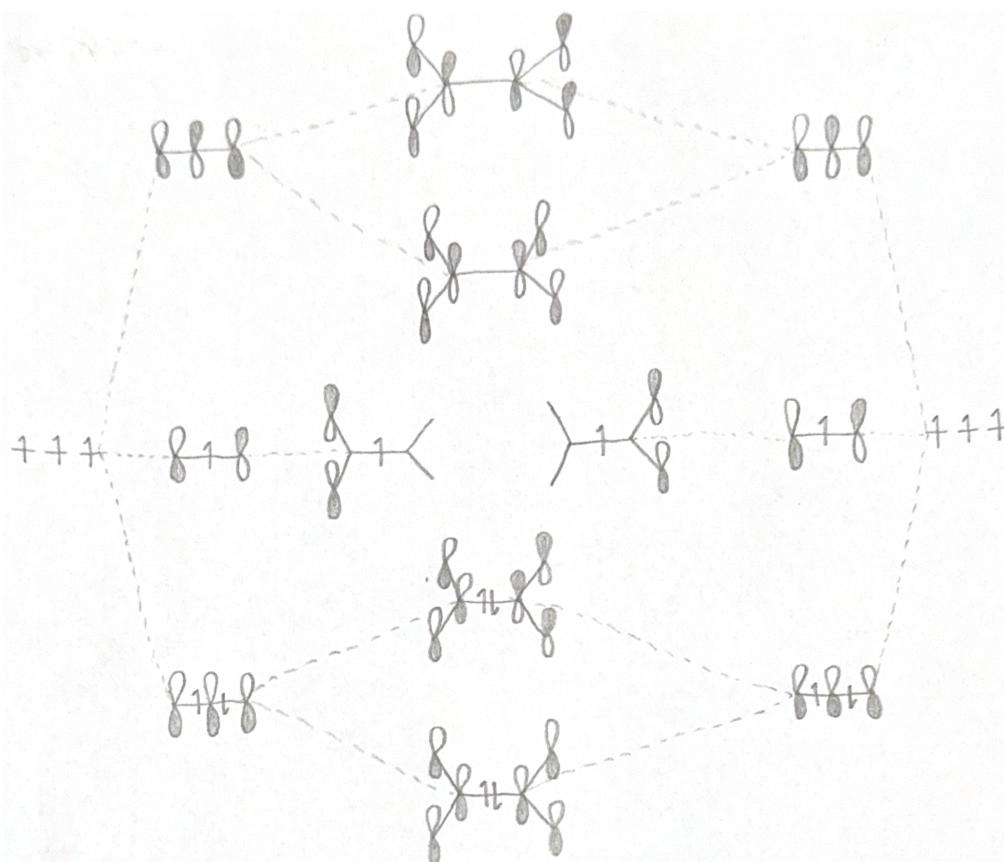
□

2. Consider the combination of two allyl fragments (**1**) joined at the center carbons, leading to diradical (**2**).



- a) Construct a π MO interaction diagram for **2** that predicts the symmetries of the combined MOs and their energies relative to carbon p -orbitals. Please assume that only interactions between AOs on adjacent atoms are significant.

Answer.



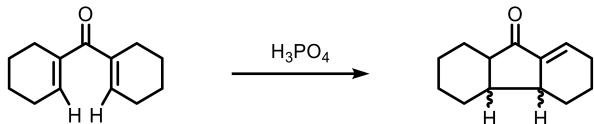
Since this MO diagram only considers π -orbitals, we begin by drawing two sets of standard allyl MOs that we will subsequently mix. Each set of allyl MOs is composed of three p -orbitals. Additionally, since there are 2 π -electrons in the double bond and 1 π -electron in the radical, each set of π -MOs is occupied by three electrons.

As we begin mixing, we only mix MOs of similar energies. In this case, that means we only mix MOs directly across. Note that we do *not* mix the middle MOs because the problem statement tells us that only MOs with “adjacent atom” interactions should mix, and these MOs have no electron density in the center where the σ -bond forms. Additionally, note that we only have electron density on one side or the other (rather than both) because if we had it on both, that would imply that we are adding or subtracting wavefunctions; in other words, the mixed orbitals are of the form $\psi_1 \pm \psi_2$ and the degenerate orbitals are of the form ψ_1, ψ_2 . \square

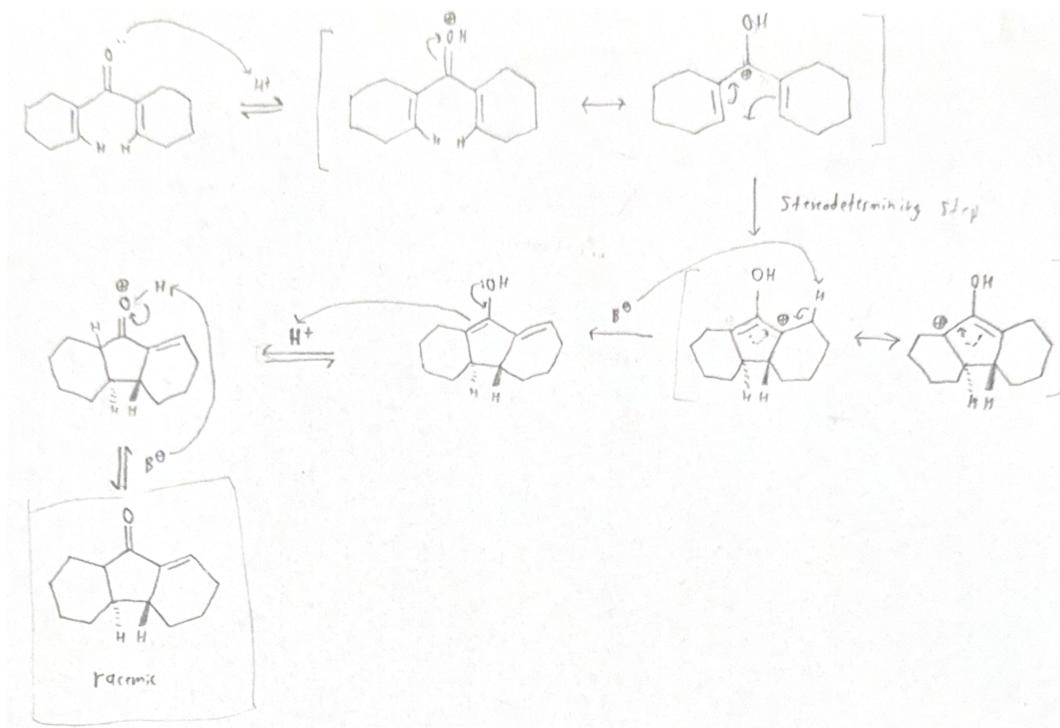
- b) Can the two radical centers delocalize via resonance? Explain using the MO diagram from part (a).

Answer. [No.] Per the MO diagram, we still have a diradical in the HOMO, and each radical electron is localized in an MO on one side of the molecule. \square

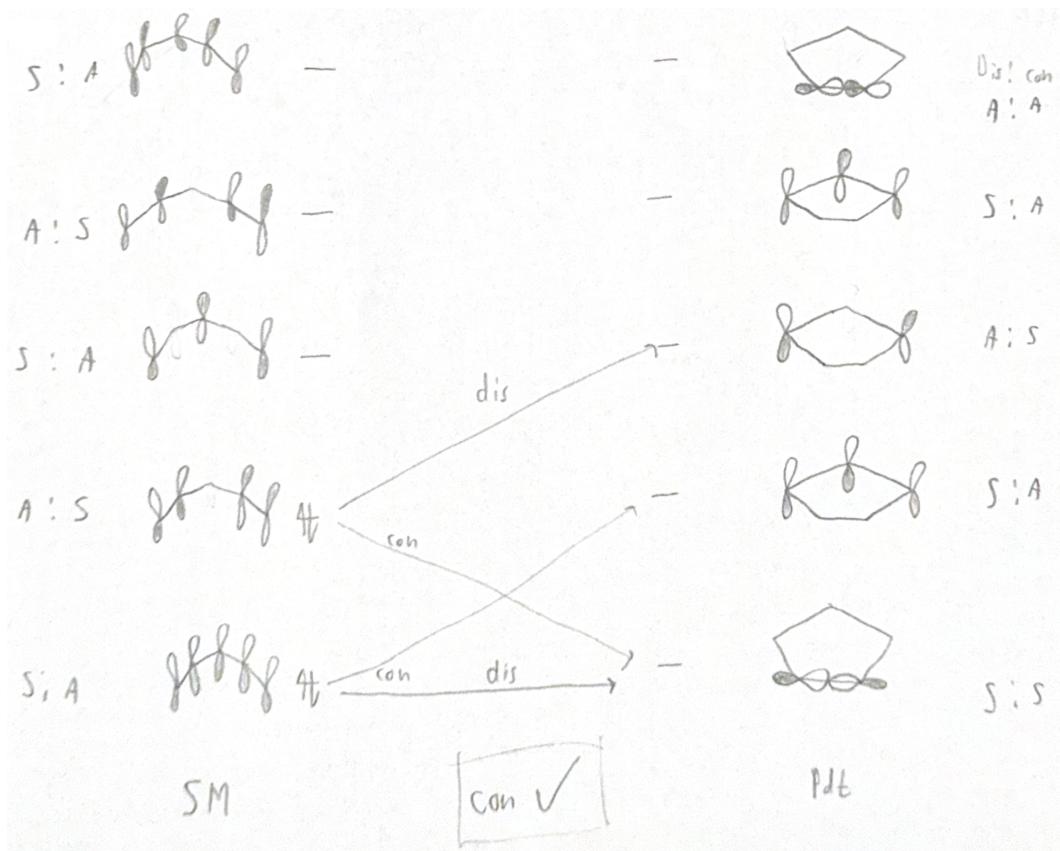
3. Predict the stereochemistry of the product and rationalize your answer based upon MO theory.



Answer.



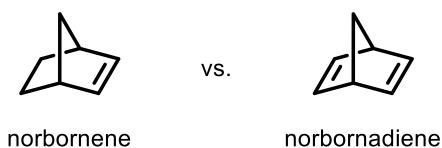
The stereodetermining step is a cationic 4π electrocyclization, more commonly known as a **Nazarov cyclization**. Note that a few steps are necessary before the cyclization to activate the substrate, and a few are necessary afterwards to convert to the final product.



The reason that the electrocyclic ring opening occurs in a conrotatory fashion is that the thermal symmetry-allowed transitions do not move electrons up in energy levels, whereas the thermal symmetry-allowed disrotatory transitions do and hence are disfavored. Note that I did not show the R groups for simplicity.

Additional notes: This problem can also be solved using FMO and rotation. □

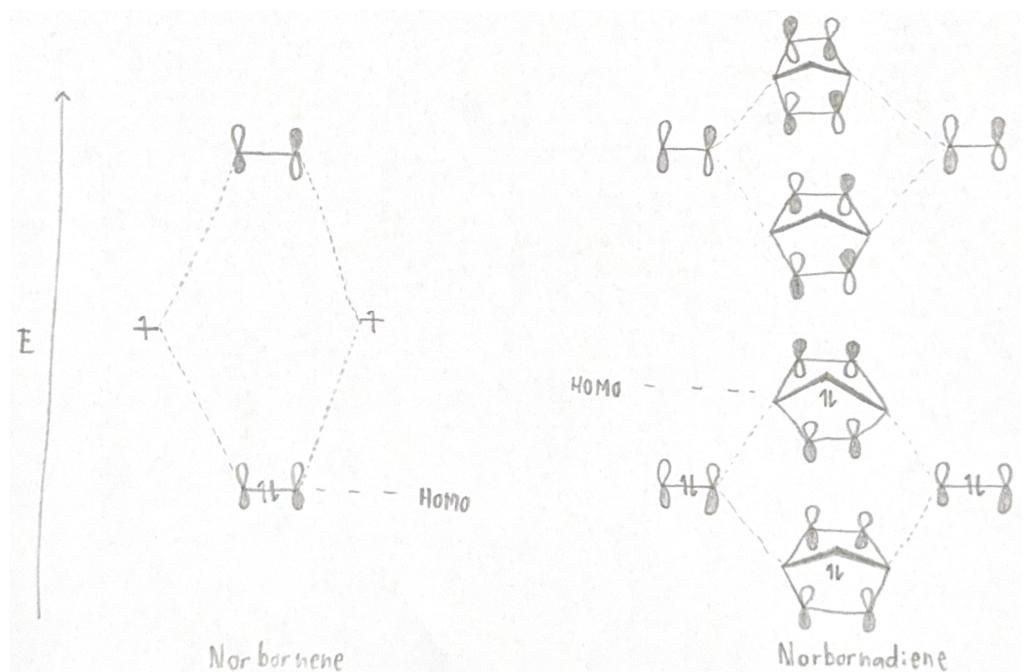
- Norbornadiene is known to be more reactive towards electrophiles than norbornene.



- Rationalize this difference using an MO diagram.

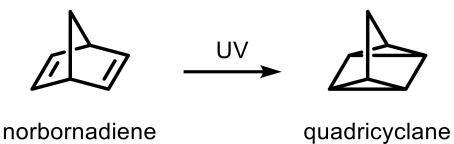
Answer. Norbornene has two p -AOs that mix into two π -MOs: One bonding and one antibonding. Norbornadiene has two pairs of these π -MOs that can then weakly re-mix through space across the molecule to form four new MOs.

After mixing, the second-lowest of these MOs (the new HOMO) will be higher in energy than the unmixed original π -MO (the old HOMO and, coincidentally, norbornene's HOMO). Essentially, this through-space mixing causes norbornadiene to have a higher HOMO than norbornene. As discussed in Q1c, species with a higher HOMO are more nucleophilic, and hence more reactive toward electrophiles.



□

- b) Norbornadiene derivatives can be converted to quadricyclane derivatives under UV irradiation. Quadricyclanes are highly strained molecules, yet they are thermally stable.

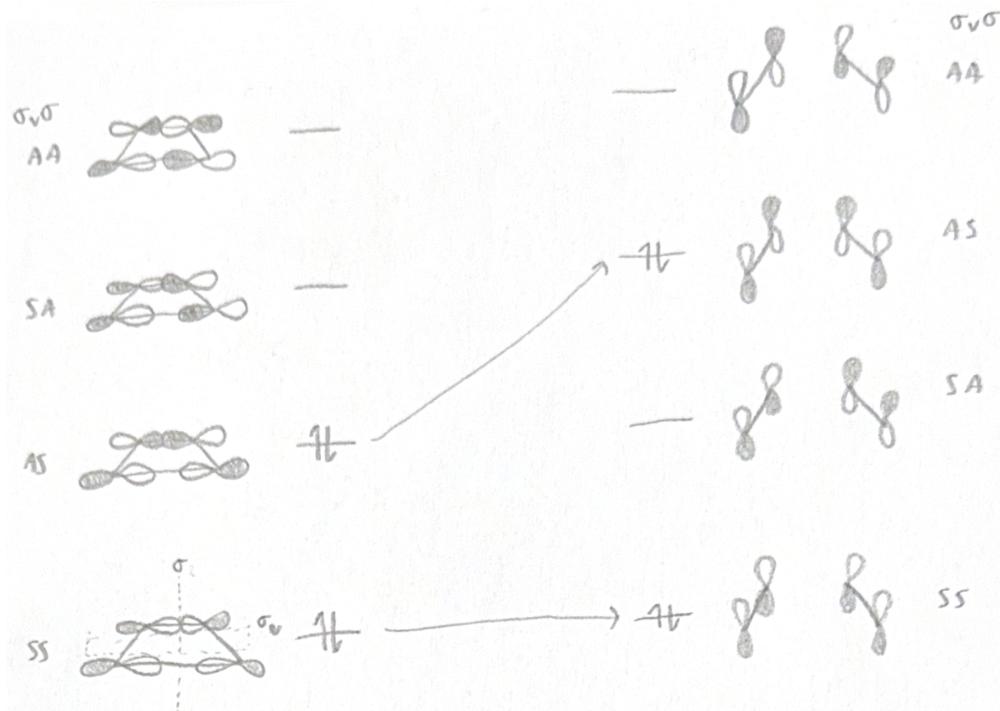


Provide a frontier MO analysis^[1] to explain why quadricyclane is thermally stable.

Answer. The reaction depicted above is a photochemical [2 + 2] cycloaddition.

To justify why the product is *thermally* stable, let's correlate the product orbitals to the starting material orbitals. Note that in doing so, we will identify the symmetry of each molecular orbital by the two persistent symmetry operations, as suggested by Anslyn and Dougherty (2006, p. 880). Namely, we will look at the σ -plane discussed in class, and a perpendicular σ_v plane running from left to right across the page. Note also that the remainder of the quadricyclane and norbornadiene rings outside of the 4-membered ring will be omitted from the following diagram for clarity.

¹Per Jonathan's 9/24 Canvas announcement, we can use *any* MO analysis discussed in lecture; in particular, we are not restricted to Fukui's FMO.



As such, we can see that a thermal cycloreversion is forbidden/disfavored because it would involve creating a high-energy excited state of norbornadiene. \square

5. Please use computational tools to complete this question. We will be using a browser-based quantum chemistry platform ([Rowan](#)) for this course.

- Create an account on Rowan (<https://rowansci.com/>) using your MIT email.
 - To learn how to submit a job on Rowan, please watch this video tutorial: <https://docs.rowansci.com/web-interface/run-a-simple-job> and/or read this overview: <https://docs.rowansci.com/web-interface/submit/geometry-optimization>.
 - More information on how to use Rowan (as well as additional tools) can be found here: <https://docs.rowansci.com/web-interface>.
- Ethane (H_3CCH_3).
 - Using any means, build a molecular model for ethane in Rowan. Then, perform a geometry optimization using the PBE0 functional and the def2-SVP basis set. Take a screenshot of the webpage before submitting the job and paste it here.
 - Note: this job should not take more than 1 minute to run (not including queue time). If it takes significantly longer, consider adjusting your initial bond lengths/angles.

Answer.

The screenshot shows the Rowan Calculation interface. In the center, there is a 3D molecular model of ethane (CC) with two carbon atoms and six hydrogen atoms. To the left of the model, there is a sidebar with a file browser showing a folder named 'CC' containing a file 'Sep 25, 2024 - Calculation'. Above the model, there are input fields for 'Calculation Name' (CC), 'Charge' (0), and 'Multiplicity' (1). On the right, there are sections for 'Folder' (Home), 'Level of Theory' (Custom, PBE0, def2-SVP), 'Corrections' (None), 'Solvent' (None), 'Engine' (Psi4 - HF/DFT), and 'Tasks' (Optimize checked, Gradient, Spin Density, Frequencies, Energy, Charge, Dipole, Optimize (TS)). At the bottom right is a 'Submit Calculation' button.

- ii. Convert the optimized structure into Cartesian (XYZ) coordinates and paste them here.

Answer.

```
C -0.75677857 -0.05411065 0.03565919
C 0.75677857 0.05411065 -0.03565919
H -1.15393947 -0.71157723 -0.75360372
H -1.23964754 0.92846958 -0.08395828
H -1.08879565 -0.46588635 1.00165110
H 1.08879566 0.46588615 -1.00165118
H 1.15393946 0.71157739 0.75360359
H 1.23964755 -0.92846954 0.08395849
```

- iii. What is the calculated optimized C–C bond distance? What is the H–C–H bond angle(s)?^[2]

Answer. C–C bond distance: 1.519 Å.

H–C–H bond angle: 107.26°.



- c) Ethyl cation (H_3CCH_2^+).

- i. Using any means, build a molecular model for the ethyl cation in Rowan. Then, perform a geometry optimization using the PBE0 functional and the def2-SVP basis set. Take a screenshot of the webpage before submitting the job and paste it here.

- Note: this job should not take more than 1 minute to run (not including queue time). If it takes significantly longer, consider adjusting your initial bond lengths/angles.

Answer.

²Per Jonathan's 9/24 Canvas announcement, provide at least 4 significant figures for bond lengths and angles. If you previously had issues obtaining these values from Rowan, please try again as the problem should be resolved now. If you are still unable to get 4 significant figures from Rowan, contact Jonathan.

The screenshot shows a web-based molecular modeling interface. On the left, there's a sidebar with a file browser showing 'Ethyl Cation' and 'CC' under the 'Home' folder. The main area is titled 'Run New Calculation' for an 'Ethyl Cation' calculation. It includes fields for 'Charge' (1) and 'Multiplicity' (1). A 3D ball-and-stick model of an ethyl cation is displayed. To the right, various calculation parameters are set: Method (PBE0), Basis Set (def2-SVP), Corrections (None), Solvent (None), Engine (Psi4 - HF/DFT), and Tasks (Optimize checked, others uncheckable). At the bottom right is a 'Submit Calculation' button.

- ii. Convert the optimized structure into Cartesian (XYZ) coordinates and paste them here.

Answer.

H -1.22084801 0.85147887 0.51800484
 C -0.64953900 -0.05423031 0.27448674
 H -0.17606995 0.13377943 -0.93834042
 H -1.18064873 -1.01496471 0.24418216
 C 0.70652007 0.01092307 0.02934683
 H 1.28037984 -0.89670040 -0.20069381
 H 1.24020579 0.96971405 0.07301367

□

- iii. What is the calculated optimized C–C bond distance? What is the H–C–H bond angle(s)?

Answer. C–C bond distance: 1.380 Å.

H–C–H bond angle: 118.43° and 105.89°.

□

- d) Now, using qualitative MO arguments based on your calculations, discuss at least two factors contributing to the differing C–C bond lengths in ethane vs ethyl cation.

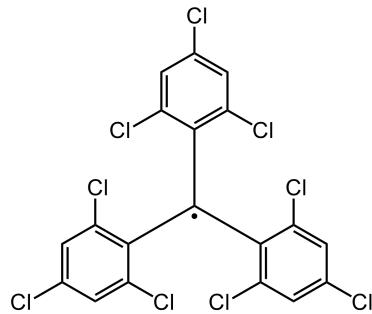
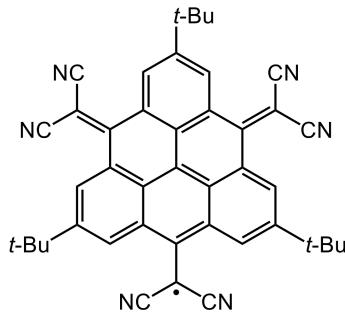
Answer. Due to hyperconjugation, there is donation from the adjacent C–H σ-bond into the carbocation's empty *p*-orbital that forms a 3c-2e bond. This donation increases the bond order of the C–C bond, shortening it compared to ethane. Additionally, the *sp*²-like bond angles mean — per the hybridization index — that the hybrid orbitals have more *s*-character and hence will be shorter.

□

2 Reactive Intermediates

10/16: The questions pertain to the material covered from Cations (Sep 24) to Selectivity (Oct 8).

1. The radicals below are known to be **bench-stable**, meaning they don't readily dimerize or get quenched by oxygen. Rationalize this observation for each.

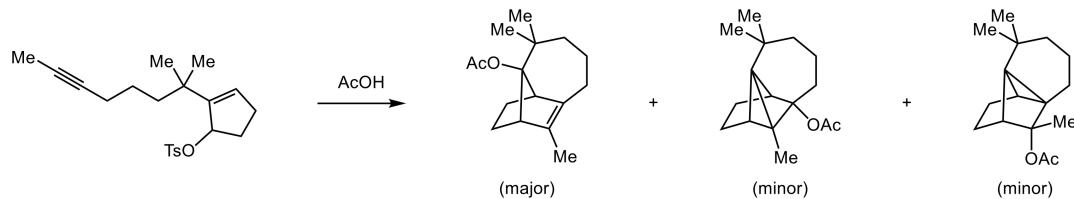


Answer. A bench-stable radical — also known as a persistent radical — is a radical that is thermodynamically high-energy (as all radicals are) but kinetically slow to react. Persistent radicals typically have some mixture of resonance stabilization and steric blocking.

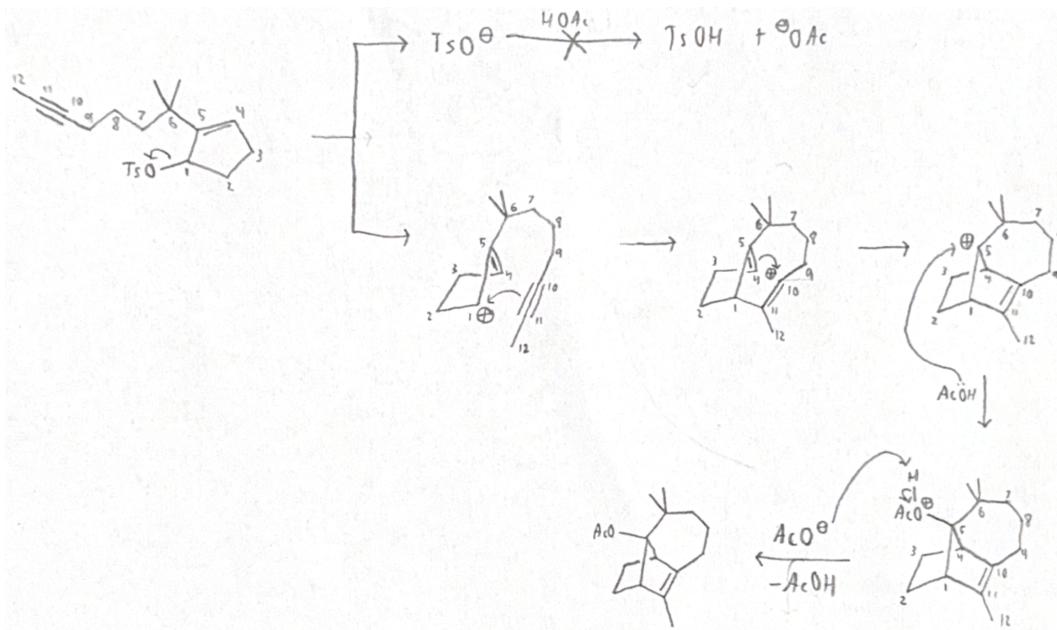
Left radical: This radical has an *extreme* amount of resonance delocalization among both the polycyclic π -system and the nitrile electron-withdrawing groups. By my count, resonance structures indicate that there should be partial radical character at 19 distinct atoms in the molecule. Thus, the spin density map should be so distributed that no one site has enough radical character to react in a kinetically efficient manner.

Right radical: Due to steric inhibition of resonance — see Anslyn and Dougherty (2006, p. 282) — this radical cannot efficiently delocalize because the conformation of the trichlorophenyl rings in space (i.e., the “paddle wheel” topology) prevents full planar double bond formation. Thus, there is more radical character on the central carbon, as drawn. However, the paddle-wheel groups sterically block access to this site, once again preventing kinetic dimerization. \square

2. a) Propose a reasonable arrow-pushing mechanism that explains the formation of the major product in the reaction below.



Answer.



Due to its high degree of resonance stabilization, tosylate is a very good leaving group. Additionally, the cation created by a tosylate departure is both secondary and resonance-stabilized. As such, I propose that the reaction mechanism will be initiated by tosylate leaving. The majority of the tosylate ions in solution will then continue to exist as tosylate (instead of deprotonating acetic acid, for example) because tosylic acid is much stronger than acetic acid.

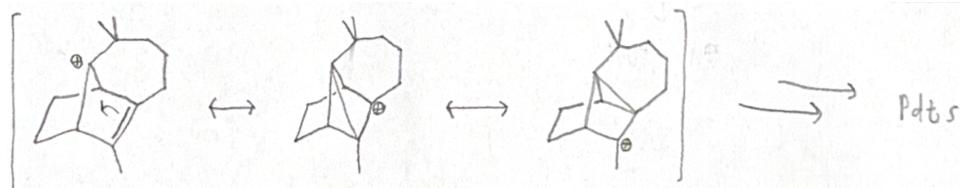
Once the first intermediate is formed, it seems like it could do a cationic [3 + 2] cycloaddition. However, such cycloadditions are thermally forbidden by the Woodward-Hoffmann rules (which we could also quickly see by drawing the HOMO of the alkyne and the LUMO of the allylic cation and observing the partial phase mismatch). As such, I propose that the allylic cation reacts intramolecularly via a two-step Gassman-type [3 + 2] non-pericyclic “cycloaddition.” Intramolecular “cycloaddition” would likely outcompete external nucleophilic attack both because it’s an intramolecular process (greater local concentration), and there aren’t any particularly *great* nucleophiles in solution. Additionally, while I have drawn the first step proceeding from a particular resonance structure, in reality, either symmetric resonance structure could react to form the same ensuing intermediate.

After the Gassman-type cycloaddition, a homoconjugation-stabilized cation will be left on the norbornene analog. This cation can then react with the best (and highest concentration) nucleophile in solution, which will be protonated acetic acid. Acetic acid has $pK_a = 4.76$ (in H_2O), so it will likely largely exist in the protonated form regardless of the solvent in which we run this reaction. Theoretically, tosylate could also react in this step to add in, but there’s much less of it, it’s a much worse nucleophile, and we’ve already discussed in class how homoconjugation speeds up tosylate departure from that position in norbornene by 5-11 orders of magnitude; so even if tosylate did add in, that process would likely be highly reversible.

Once acetic acid adds in, its proton will be highly acidic and easily deprotonated by a base in solution. This could be the solvent, but it could also be AcO^- , TsO^- , or AcOH . Among these choices, I feel like AcO^- would do the deprotonation the most often because even though there's not much of it present, there will still be more of it than TsO^- (and it's more basic than TsO^-) and for AcOH_2^+ , $pK_a = -6.1$. This deprotonation yields the final product. \square

- b) Suggest how the minor products could be formed and draw the key intermediate(s) involved.

Answer.



I suggest that the final cation before AcOH adds in has partial nonclassical, 3c-2e character. It will still favor the homoconjugation-stabilized form drawn in part (a) — accounting for why that gives the major product — but a Mulliken partial charge on the other carbons could also lead to AcOH addition to those resonance forms followed by deprotonation, as drawn in part (a). \square

3. Which of the following two compounds is more acidic (lower pK_a)? Compare the acidity of the protons indicated red. Rationalize your answer.

a)



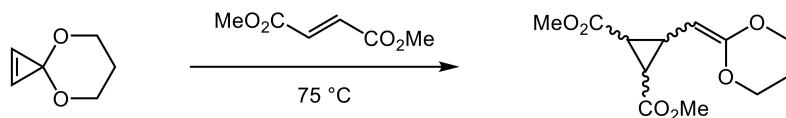
Answer. Neither esters nor amides are particularly enolizable since the lone pairs from the adjacent oxygen/nitrogen atoms compete with the resultant anion to delocalize into the carbonyl; this is an example of the resonance saturation effect described on Anslyn and Dougherty (2006, p. 282). However, the ester will be more acidic than the amide because the oxygen holds onto its electrons more tightly than the amide, thus sapping less of the carbonyl's potential ability to withdraw electrons. □

b)

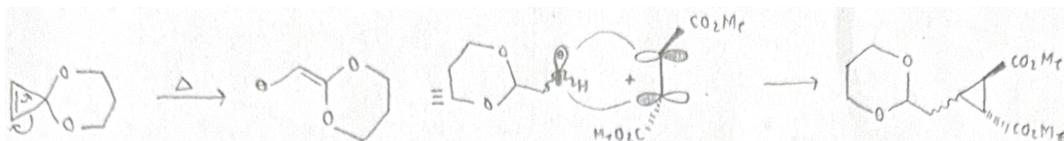


Answer. This regime is also governed by a resonance saturation effect. In both lactone and ester, the non-carbonyl oxygen will be sp^2 -hybridized so that one of its lone pairs can conjugate with the carbonyl (specifically, the carbonyl's π^* -orbital). However, in the drawn conformation of the ester, the other oxygen lone pair can *also* delocalize through $n_O \rightarrow \sigma_C^*$ donation. This secondary interaction is not possible in the lactone, which is conformationally locked such that the other oxygen lone pair points away from the carbonyl's σ^* -orbital. The net effect is that the carbonyl in the lactone is less electronically saturated than the carbonyl in the ester, so the lactone anion can delocalize more effectively into the lactone carbonyl. But then the lactone can more readily stabilize the conjugate base, so the lactone is more acidic. □

4. a) Suggest a reasonable mechanism for the following transformation.



Answer.



The elevated temperature suggests — as a first step — either a homolytic bond cleavage (as in the case of AIBN) or some kind of pericyclic reaction. The cyclopropene bonds will likely be very strained, but all the same, the bonds will likely not be as weak as AIBN's bonds. As such, I propose a retro-anionic 4π electrocyclic reaction as a first step. This will move the double bond to its final place and produce a *singlet* carbene. Moreover, the carbene will remain a singlet because of the π -donor ability of the oxygen heteroatoms through the conjugated system. More accurately, when the oxygen atoms and π -system mix with the carbene **D**-orbital, they stabilize themselves and raise the energy of the empty **D**-orbital, making it more energetically favorable to pair electrons in the **C'**-orbital. There would also be an argument to make — based on class content — that conjugation with the π -bond favors the triplet state, but I believe that the π -donor ability from two oxygens (as described above) will outweigh this competing effect.

This singlet carbene can then be approached (on either face!) by the other reactant. I predict that the carbene will react with its HOMO since it is receiving electron density from a π -donor, while the other reactant will react with its LUMO since it has two adjacent ester EWGs. With the phasing match of a nonlinear approach, the next step will be a chelotropic $[2 + 1]$ cycloaddition, forming our product. The *trans*-EWGs of the alkene will yield a *trans*-product, but — as mentioned above — we will get some of both diastereomers with respect to the other bond because the carbene has two faces open to nonlinear approach. □

- b) Discuss the stability of the intermediate(s) and predict the stereochemistry of the product.

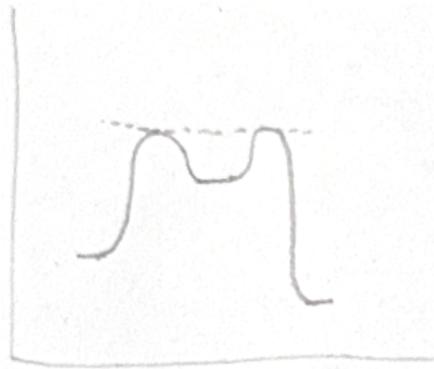
Answer. See part (a).

□

5. Draw potential energy diagrams for each of the following situations. Use dashed horizontal lines to indicate equivalent energy levels.

- a) A single substrate can undergo two reactions with equal rates but different product stabilities. What reaction conditions would you use if you wanted a mixture of products? What reaction conditions would you use if you wanted a single product, and which product would you expect?

Answer.



Draw the substrate at an arbitrary energy level. Since both reactions have equal rates, draw humps with equal ΔG^\ddagger to both sides of it, one for each reaction. Then curve the humps down to products at different energy levels.

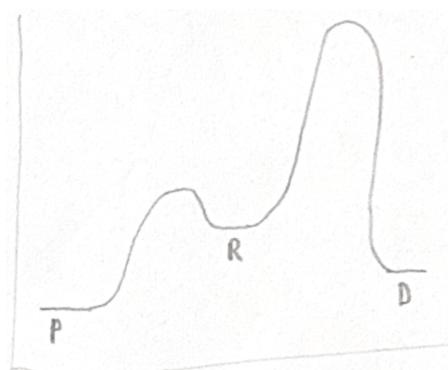
If I wanted a mixture of products (i.e., the kinetic products irreversibly formed through the energetically equivalent transition states), I would use short reaction times and low temperature.

If I wanted a single product (i.e., the thermodynamic product formed irreversibly along with a reversibly formed alternate product), I would use long reaction times and high temperature.

It follows that I would expect the more stable product to be formed at the end. □

- b) The formation of a kinetically stable radical from a precursor and dimerization of that radical.

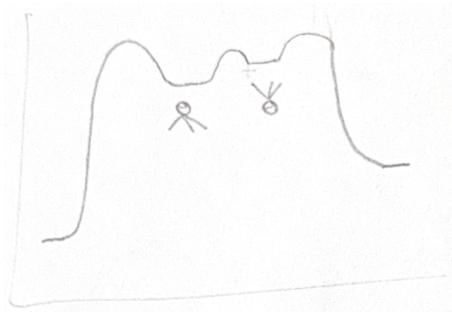
Answer.



The precursor (P) goes over a slight energy hump to become a relatively higher energy radical (R). Once the radical is isolated, it is kinetically stable, meaning that there must be a *very* high energy barrier to it forming the dimer (D). Note that the dimer would still be more *thermodynamically* stable than the radical (because persistent radicals are still *radicals*; they don't want to exist). Also, we would probably need more information to determine *for sure* whether the dimer or precursor is more thermodynamically stable, but I drew it higher in energy because I feel like in a number of systems (envisioning TEMPO, for instance), the steric blocking groups would seriously clash in a dimer, making it less thermodynamically stable than whatever precursor we're using (e.g., TMP). □

- c) The stereoselective protonation of a tertiary carbanion.

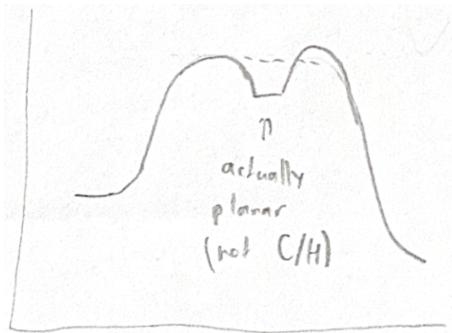
Answer.



Since it can generate two stereoisomers, the tertiary carbanion must be able to be protonated on either of its prochiral faces. As such, I propose a Curtin-Hammett regime in which the tertiary carbanion is in equilibrium between two inversion states. The inversion state that is slightly higher in energy will be the one that brings the more sterically bulky groups closer together. From here, we will have protonation that will likely be fairly low-barrier (as it gets rid of the reactive intermediate anion), and likely result in fairly equal-energy products. However, the higher energy anion will have its bulky groups closer together, meaning that the anion is more exposed for *slightly* easier protonation, and it will also probably form the *slightly* less stable product since, again, the bulky groups will be closer together. This is like Curtin-Hammett Scenario 2. \square

- d) Starting from one pure diastereomer, the epimerization of the alpha position of a ketone under acidic conditions to form a mixture of products.

Answer.



If the ketone can epimerize at the α -position, the ketone must be chiral at that α -position. Additionally, such an epimerization will proceed through an enolate intermediate. This enolate intermediate will be *actually* planar at the deprotonated α -position because the enolate carbanion is resonance-stabilized. In particular, since this high-energy intermediate is actually planar, it does not undergo inversion like in part (c), so we are *not* under Curtin-Hammett kinetics. Then, like in part (c), we'll have quicker protonation at a less sterically hindered face leading to a less stable product, and slower protonation at a more sterically hindered face leading to a more stable product. \square

References

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