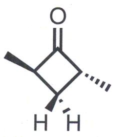
386J FINAL EXAM
December 16th, 2014

Name: KEY

1	/12
2	/4
3	/3
4	/6
5	/7
6	/9
7	/6
8	/9
9	/7
10	/5
11	/6
12	/8
13	/8
14	/16
15	/28
16	/12
17	/6
18	/8
19	/8
20	/16
21	/11
22	/11
Total	/206

1. (12 pts) Use the following molecules A and B to answer the questions below.

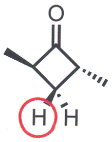
A



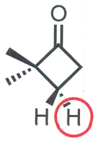
B

a) Label the faces of the carbonyl groups as Re or Si. If you can't say, explain.	neither, not pro-chiral	Si
b) Are the π-faces of the carbonyl groups enantiotopic, diastereotopic or homotopic?	homotopic	enantiotopic
c) Are the two hydrogen atoms indicated in each molecule enantiotopic, diastereotopic or homotopic?	homotopic	enantiotopic
d) When nucleophilic attack by CN^- occurs on the carbonyl group, does it lead to one compound, a racemic mixture or one stereoisomer in excess?	one compound	racemic
e) Is the molecule chiral or achiral?	chiral	achiral
f) Is the circled hydrogen atom (see below) pro-R or pro-S? If you can't say, explain.	neither, not pro-chiral	pro-S

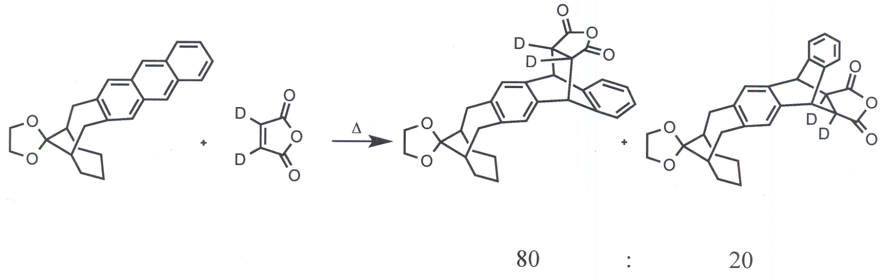
A



B



2. (4 pts) For the following Diels-Alder reaction, answer the questions.



a) Is this reaction stereoselective, stereospecific or neither?

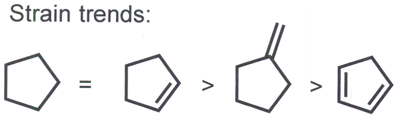
Stereoselective

b) What type of kinetic isotope effect would you expect in this reaction at the position where the "D" is drawn?

2° inverse

3. (3 pts) A strain trend among several five-membered ring molecules is given below. Explain why you observe this trend.

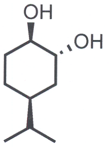
Strain trends:



Decrease in eclipsing strain (torsional strain) compensates for the small increase in angle strain.

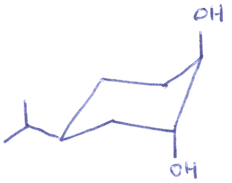
Ring strain = torsional strain + angle strain

4. (6 pts) Let's examine the following molecule, 4-isopropylcyclohexane-l,2-diol, as drawn.

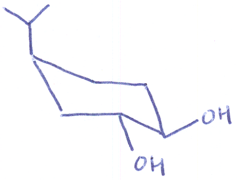


	A value (kcal/mol)
OH	1.04
$CH(CH_3)_2$	2.21

a) Draw both chair conformations of the above isomer of 4-isopropylcyclohexane-l,2-diol.



A



B

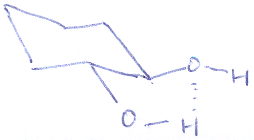
b) Which conformation do you predict is more stable and by how many kcal/mol?

A is more stable by 0.13 kcal/mol.

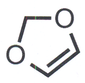
$2.21 - (2 \times 1.04) = 0.13$

c) Experimentally the conformation with both hydroxy groups equatorial is found to be more stable by 1.9 kcal/mol than the answer given in part b). Where does the extra stability arise from?

Intramolecular hydrogen bonding

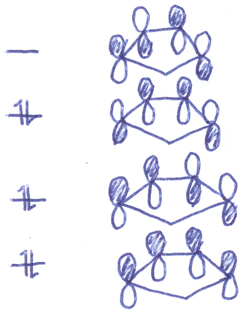


5. (7 pts) 1,3-Dioxole is found to puckered with a dihedral angle of 24°. The molecule was expected to be planar because of an absence of any torsional strain.



1,3 - Dioxole

a) Draw a molecular orbital diagram of the π-system of hypothetically planar 1,3-dioxole using p-orbitals on the oxygens with the p-orbitals on the carbons. Populate with electrons.

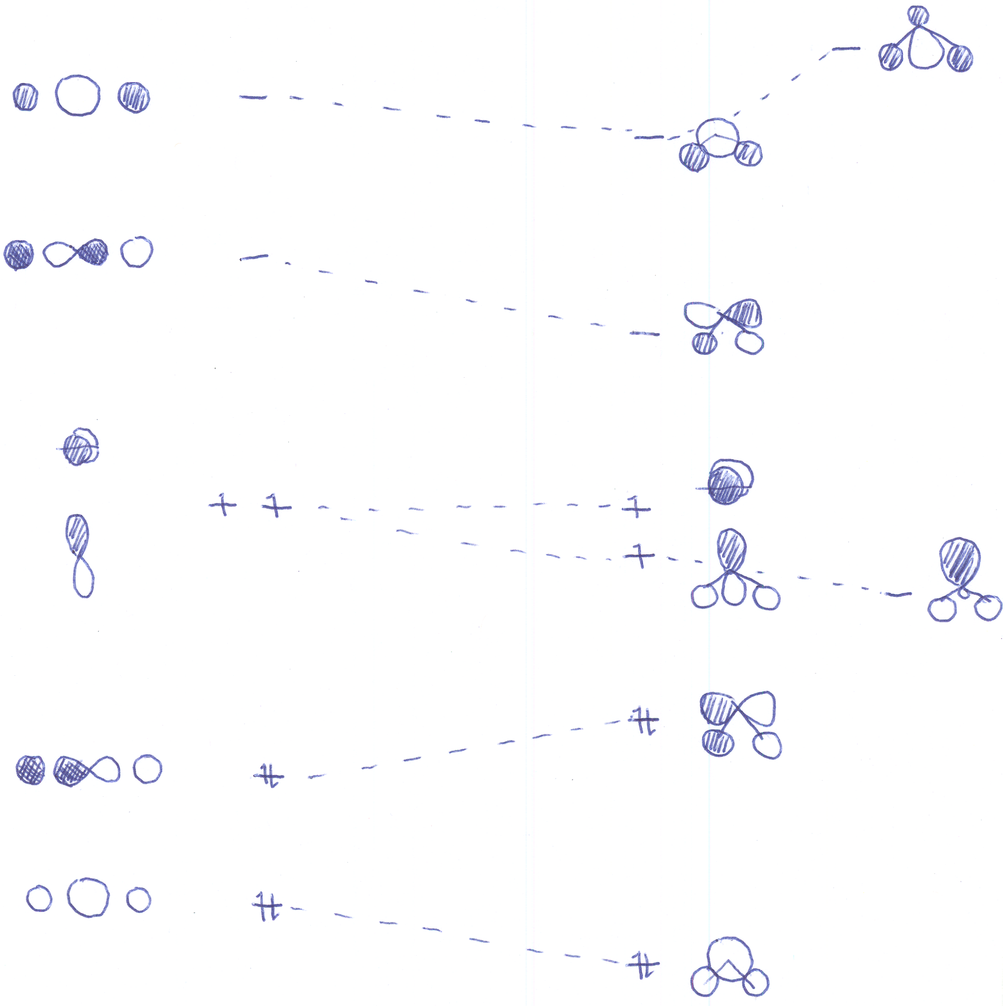


b) Using your answer from part a), explain why the molecule does not want to be planar and thus is puckered.

The π-system contains $6e^-$, two placed in antibonding orbitals. Puckering would decrease e^- density in the π-system and allow for some overlap between the p-orbitals on oxygen and σ^*_{C-O}. The overall effect is stabilizing.

6. (9 pts)

a) Draw the Walsh diagram for a planar to a bent CH_2 fragment. Show all orbitals and any mixing that may result.

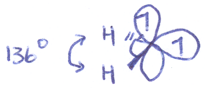


b) Using the diagram from part a), what would you expect the geometry to be for singlet carbene and for triplet carbene? Explain.

- Singlet CH_2 prefers a bent geometry.

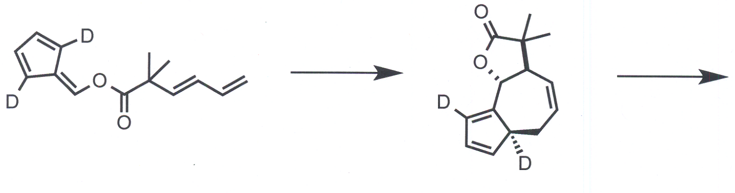
- CH_2 is stabilized by bending because both electrons move into the lower energy sp^2 hybrid orbital.

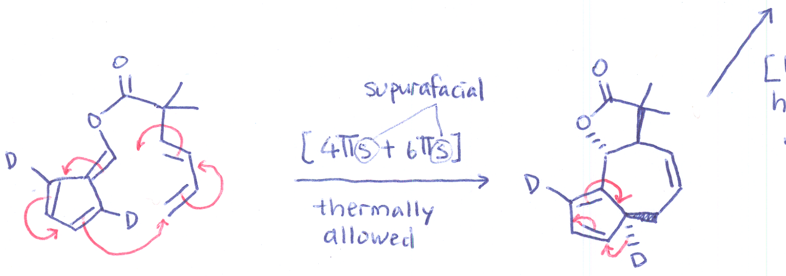
- Triplet CH_2 prefers a geometry that is not so bent, and more linear.



- Both electrons with same spins. They cannot occupy same orbital.
- Only one orbital is stabilized by bending.

7. (6 pts) Show arrow pushing for both pericyclic reactions given below. Label each pericyclic process as suprafacial or antarafacial. State if the reactions are allowed or forbidden as shown.





supurafacial

[4πⓢ + 6πⓢ]

thermally allowed

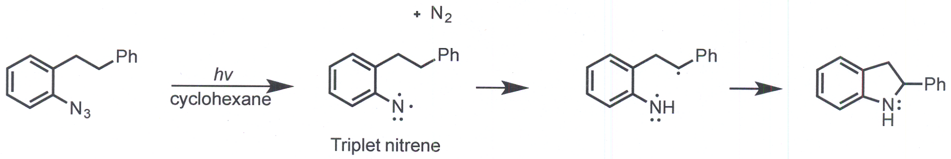
supurafacial

[1ⓢ,5ⓢ]

hydrogen shift

"allowed"

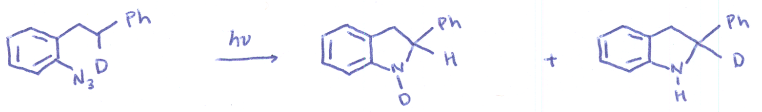
8. (9 pts) Irradiation (>300 nm) of the following azide compound in cyclohexane exclusively afforded 2-phenylindoline, which appeared to be a primary photoproduct.



Propose three experiments (isotope labeling, stereochemical analysis, and radical clock) that would support the intramolecular C-H insertion of a triplet nitrene as shown above. Briefly **explain** how each experiment tests the mechanism *by drawing* what the starting material would be, and **draw** what would be the outcome of each experiment.

Experiment 1 (Isotope labeling):

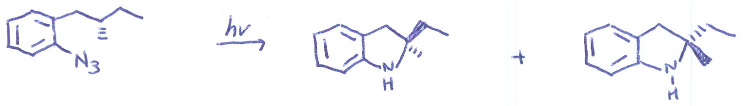
Measurment of the KIE → small deuterium isotope effects expected



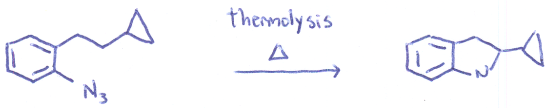
preferred product.

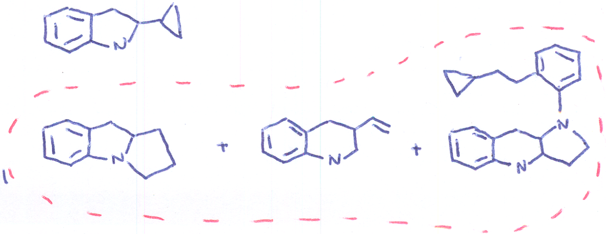
Experiment 2 (Stereochemical analysis):

The enantiomeric purity of starting azide will almost completely be lost during the intramolecular CH insertion of the nitrene.



Experiment 3 (Radical clock):

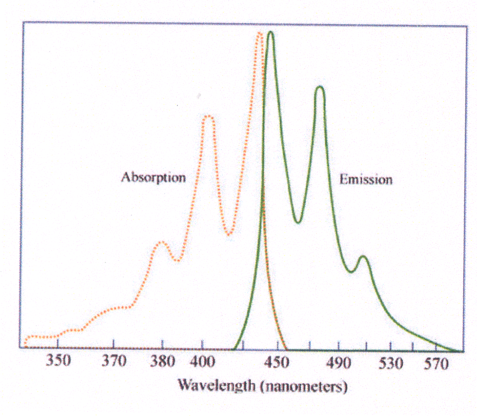


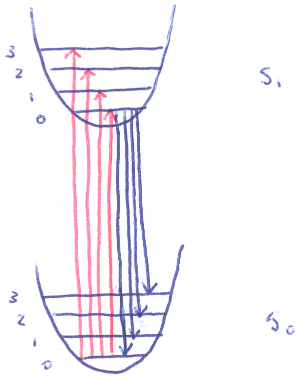


- Ring-opened products, which can be produced through the cyclopropylcarbonyl radical rearrangement
- Large rate constant estimated for ring-opened reaction

9. (7 pts)

a) A general diagram of the absorption and emission spectra for a fluorophore is shown below. Explain why they are approximately a mirror image of each other. Recreate a simplified Jablonski diagram to help explain your answer.

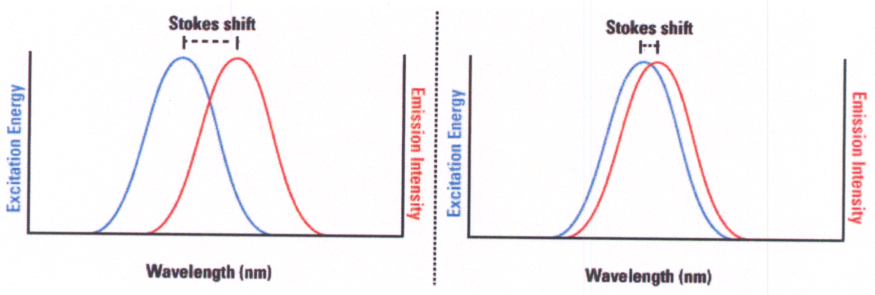




The emission spectrum of a fluorophore is typically a mirror image of the S_0 to S_1 absorption spectrum transition. This is due to the fact that electronic excitation does not seriously alter the geometry of the nucleus and the spacing of exited state vibration levels is similar to that of the ground state.

$(0 \rightarrow 3^*)$ $(0^* \rightarrow 3)$

b) Below are the absorption and emission spectra of a fluorophore. What is the origin of the Stokes shift? Explain your answer.

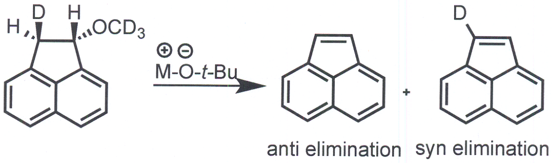


The stokes shift may arise from enviromental effect (different solvation etc.) as well as from a change in the geometry of the emitting excited state.

c) What is a disadvantage of using fluorophores with very small Stokes shifts (right panel)?

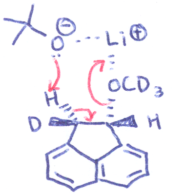
Smaller stokes shift exhibit background signal due to the smaller difference between excitation (absorption) and emission wavelengths.

10. (5 pts) The following is an elimination reaction involving an E1cB mechanism. The starting molecule undergoes deuterium exchange with solvent in competition with elimination. When various salts of the base *tert*-butoxide (M^+-$^-$O-*t*-Bu) are used, the syn/anti elimination ratio decreases in the order $M^+ = Li^+ > Na^+ > K^+ > (CH_3)_4N^+$. Rationalize the observed ratio of products.



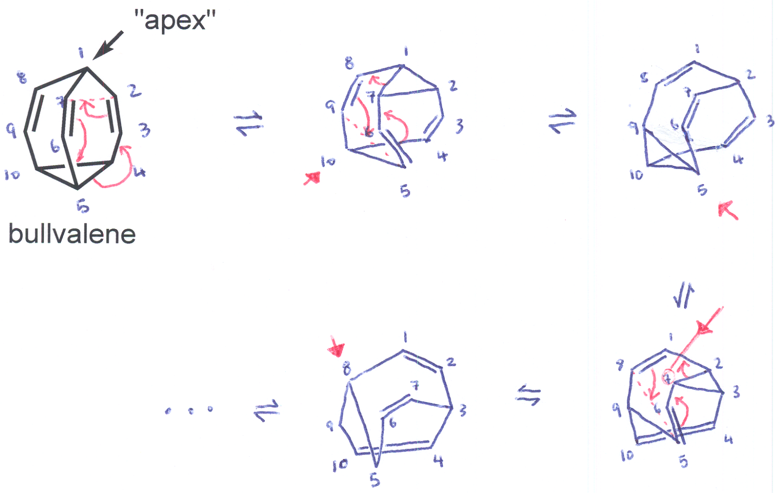
Syn elimination is favored with the Li$^+$ counteranion because the cation is strongly ion-paired with both the butoxide base and the departing methoxide leaving group. Therefore, the base removes a proton from the same face of the newly formed double bond as the leaving group departs.

As the counteranion become less coordinating, anti-elimination dominate because the reaction more resemble E2.



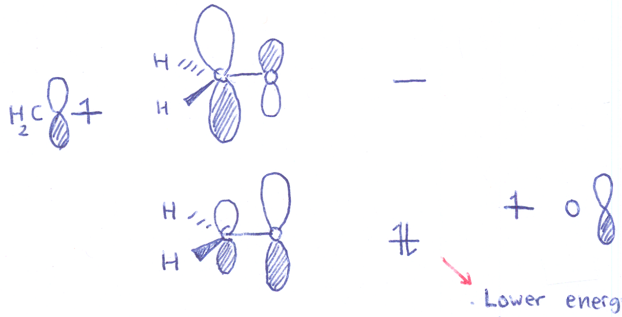
11. (6 pts) The following molecule is called bullvalene. The name, bullvalene, is derived from the nickname of William "Bull" Doering who predicted its properties in 1963. As a fluxional molecule, bullvalene is subject to degenerate Cope rearrangements, with the result that all carbon atoms and hydrogen atoms appear equivalent on the NMR timescale. The number of possible isomers is 10, since any of the 10 carbon atoms may be at the "apex".

Show THREE different (out of 10) Cope reactions with arrow pushing, thereby demonstrating how these rearrangements ultimately make all the “C”s and “H”s equivalent. This problem will require some artistic talent, so be careful to make the pictures clear to the graders. You could number the C’s if you like.



12. (8 pts) This problem is meant to tie together some knowledge from Chapter 1 with Chapter 16.

a) Draw the bonding and antibonding orbitals for the π-bond in formaldehyde, showing in your cartoons the differences in contribution of the p-orbitals from the C and O atoms to the bonding and antibonding orbitals.

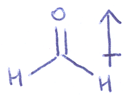


The orbitals of oxygen is lower in energy.

· Lower energy orbital resemble the most with the starting closest in the energy

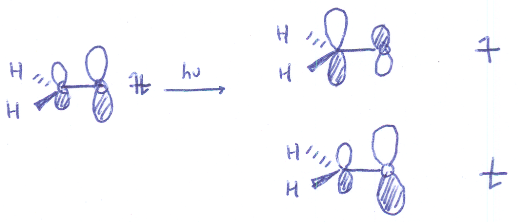
· mostly character of 'O'

b) Draw a dipole arrow on formaldehyde, and then explain why the orbitals you drew above are consistent with this.



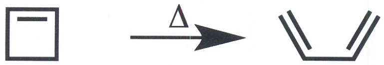
The preferred charge distribution will have the positive charge on less electronegative atom (carbon) and the negative charge on the more electronegative atom (oxygen).

c) The dipole moment for formaldehyde is 2.3 Debye (D) units. However, the first singlet excited state (S_1) for formaldehyde only has a dipole moment of 1.5 D. Explain why there is such a difference using the orbitals you drew in part a).



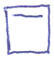
Having an electron in the antibonding orbital reduces overall dipole moment.

13. (8 pts) The following is the electrocylic ring opening of cyclobutene to butadiene.



a) Calculate the heats of formation of cyclobutene and butadiene using the Benson group additivities given below.

Group	ΔH_f^o (kcal/mol)
$C\text{-}(H)_3(C)$	- 10.20
$C\text{-}(H)_2(C)_2$	- 4.93
$C\text{-}(H)(C)_3$	- 1.90
$C_d\text{-}(H)_2$	6.26
$C_d\text{-}(H)(C)$	8.59
Correction	
cyclobutenyl strain	32



$C_d-(H)(C)$ 8.59 x 2 = 17.18

$C-(H)_2(C)_2$ -4.93 x 2 = -9.86

cyclobutenyl Strain correc +32.0

39.32 Kcal/mol

$C_d-(H)_2$ 6.26 x 2 = 12.52

$C_d-(H)(C)$ 8.59 x 2 = 17.18

29.70 Kcal/mol

b) What is ΔH° for this electrocyclic ring opening?

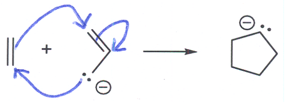
29.70 Kcal/mol − 39.32 Kcal/mol = − 9.62 Kcal/mol

c) If ΔS° is negligible, estimate the K_{eq} value at room temperature (albeit it requires high temperature to get the reaction to occur on a reasonable time scale).

$K_{eq} \approx 10^{7.07}$

14. (16 pts) Consider the pericyclic reaction below.

a) Draw proper arrow pushing for the following cycloaddition reaction keeping track of all bonds and lone pairs.



b) Draw an orbital correlation diagram for the suprafacial-suprafacial reaction of an allyl species with an olefin to give the corresponding cyclopentyl species, **and** indicate whether the reaction is allowed or forbidden for the cation, anion, and radical.

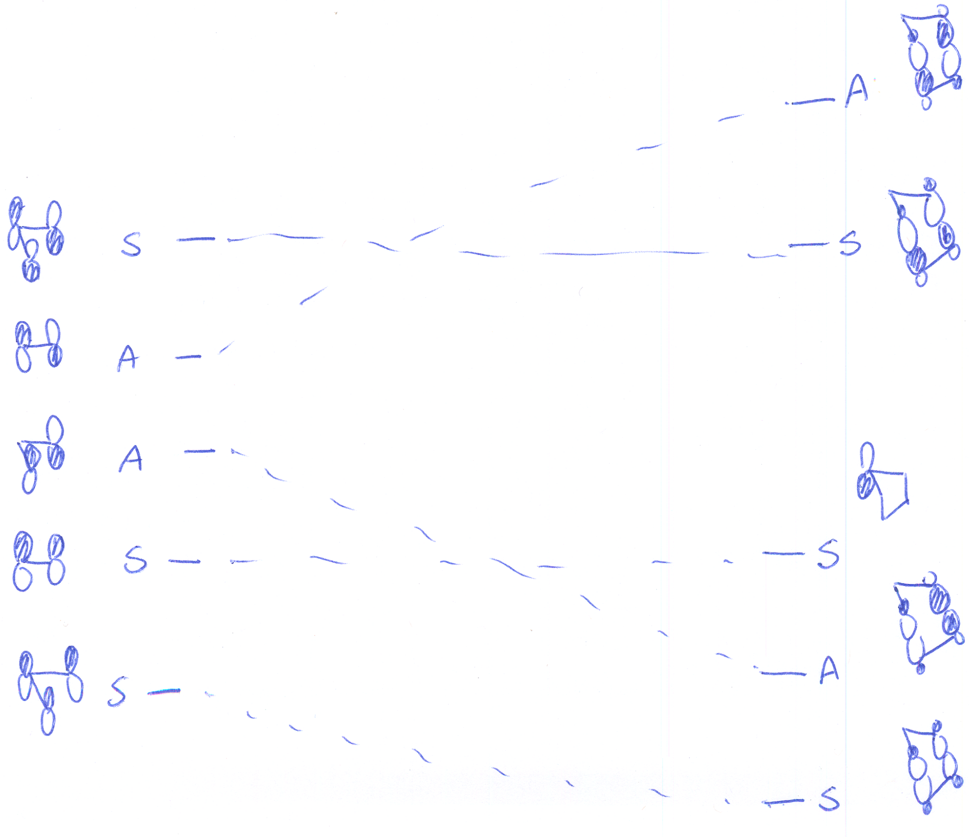
* = ⊕ ⊖ ·

Allowed or Forbidden?

Cation: forbidden

Radical: forbidden

Anion: allowed



c) For allyl cation and anion, use the generalized orbital symmetry rule (Woodward-Hoffman rule) to determine whether each case is allowed or forbidden in the same approach geometry as in part b. Show how you arrived at your conclusions.

Cation:

$\pi 2s + \pi 2s$

$1 + 1 = 2$ forbidden

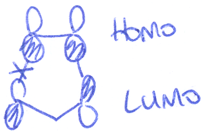
Anion:

$\pi 2s + \pi 4s$

$1 + 0 = 1$ allowed

d) For allyl cation and anion, draw the orbitals and use FMOT to determine whether each case is allowed or forbidden in the same approach geometry as in part b. Show how you arrived at your conclusions using orbital diagrams.

Cation:



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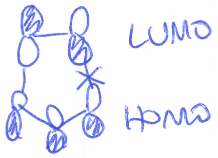
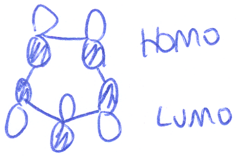


forbidden

Anion:



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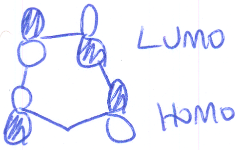
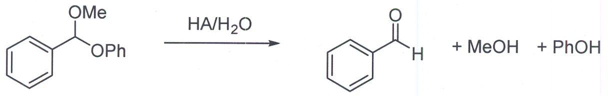


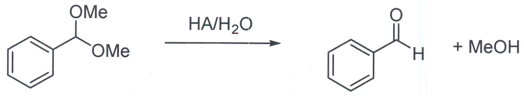
allowed

15. (28 pts) Consider the acid-catalyzed hydrolysis of the following acetals.

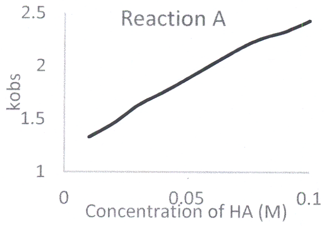
A



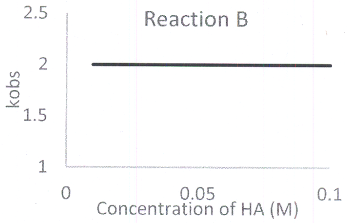
B



a) From the plots given below, 1) write the kind of acid catalysis for each reaction under the corresponding plot, and 2) in the spaces provided below, write mechanisms that reflect your choices. You do **not** need to show steps past the rate-determining step in each mechanism! Label the rate-determining step in your mechanisms written below.

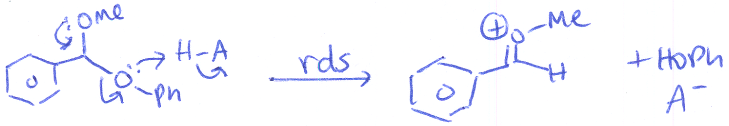


General

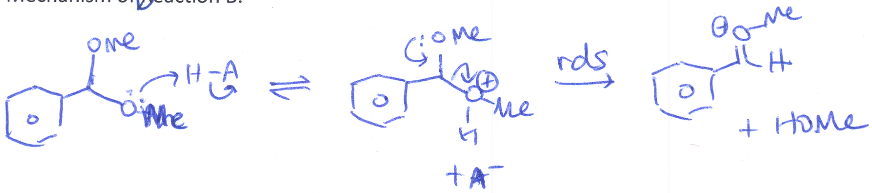


Specific

i) Mechanism of reaction A:



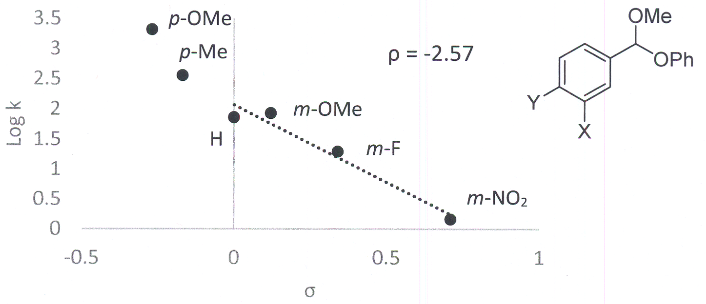
ii) Mechanism of Reaction B:



iii) Give a reason for why reactions A and B proceed with different mechanisms.

OMe is a worse LG than OPh + must be completely protonated before it can leave

b) Here is a Hammett plot for Reaction A. The authors calculated ρ from only the meta (X) substituted derivatives, since including the para (Y) derivatives introduced curvature to the plot.



i) What does the ρ value tell you about the activated complex (i.e. transition state) at the rate determining step?

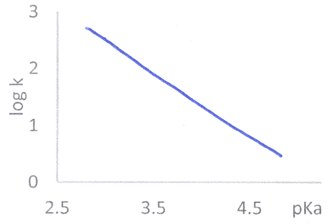
significant positive charge is building
(i.e. oxonium ion in mechanism A)

ii) How would you interpret the curvature of the Hammett plot?

- TS changes in response to the extent of charge development
- resonance effects

(mechanism change would be a sharp break)

c) Sketch the Brønsted plot you would expect to see for Reaction A in the space below.

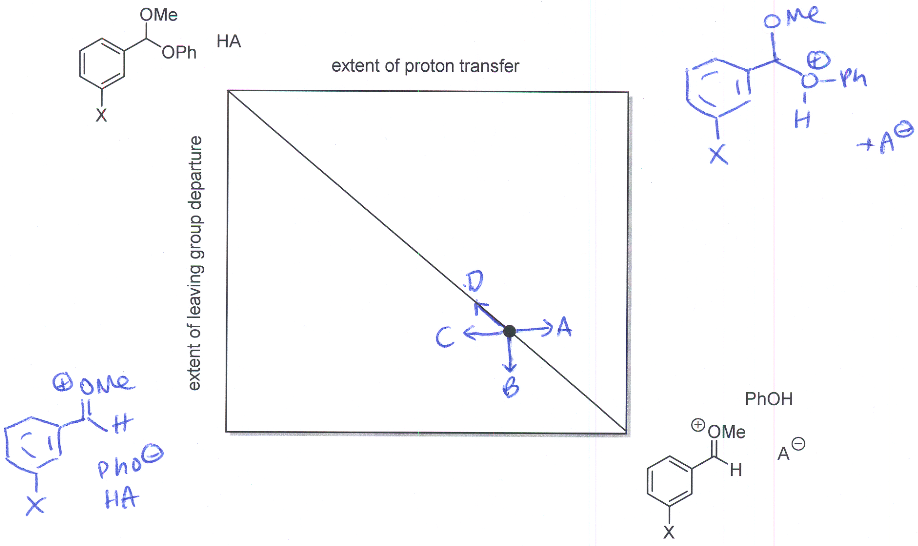


When the meta (X) substitution of the acetal is varied, α varies as shown in the table below. Rationalize the trend.

Substituent	α
m-NO_2	1.05
m-F	0.92
m-OMe	0.78
H	0.77

less proton transfer at TS is necessary when the C-O bond is broken more easily; $\oplus$ charge is stabilized by EDG + destabilized by EWG

d) Fill in the remaining two corners of the More O'Ferrall Jencks diagram for Reaction A below. The transition state is marked by the dot along the diagonal.



i) Show how the position of the transition state will change when X is changed from H to NO_2. Label as A. Explain your choice and why it makes sense.

destabilization of oxonium ion by EWG requires more protonation @ TS

ii) Show how the position of the transition state will change when HA is changed from chloroacetic acid to acetic acid. Label as B. Explain your choice and why it makes sense.

weaker acid requires more LG departure

iii) Show how the position of the transition state will change when X is changed from H to OMe. Label as C. Explain your choice and why it makes sense.

stabilization of oxonium ion by an EDG requires less protonation

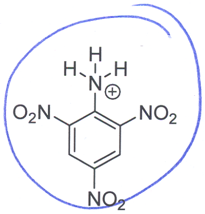
* if you answered this differently based on the info in the previous table, you were given credit if you could rationalize it

iv) Show how the position of the transition state will change when the solvent is changed from acetone to water. Label as D. Explain your choice and why it makes sense.

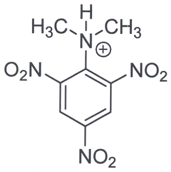
more polar solvent stabilizes oxonium ions (all of them); both less protonation + less LG departure required; more exothermic rxn/less endothermic

16. (12 pts) Predict which is the stronger acid in each pair and explain why briefly.

a)

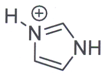


or



methyl groups prevent planarity + hence resonance stabilization of the lone pair

b)



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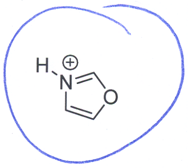
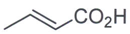


O doesn't stabilize the ⊕ charge as effectively as N due to its greater electronegativity

c)



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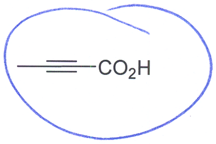
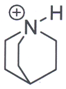


hybridization | s-character

d)



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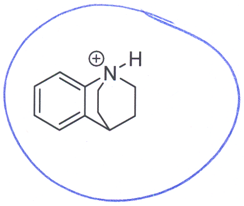
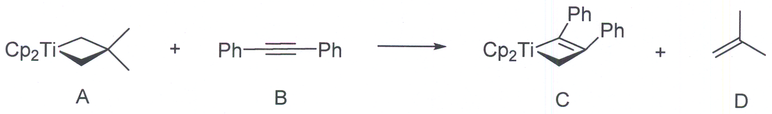


induction from pheny ring

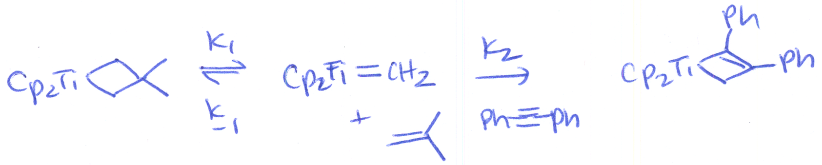
not resonance due to distorted bond angles

17. (6 pts) The following reaction is first order in metallocyclobutane (A). The reaction is first order in diphenylacetylene (B) at low concentrations but becomes zero order in diphenylacetylene (B) when 20 or more equivalents are used. When isobutylene (D) is added, the rate slows down.



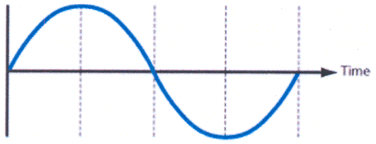
Derive a rate law that conforms to these data, **and** write a mechanism that is consistent with this information. You do **not** need to show arrow pushing in your mechanism, rather simply show the steps with the appropriate intermediates, reagents, and rate constants (e.g. k_1, k_{-1}, k_2, etc.) over the arrows.

$$\text{rate} = \frac{k_1 k_2 [A][B]}{k_{-1}[D] + k_2[B]}$$

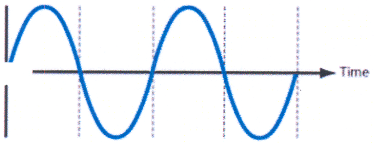


18. (8 pts) A few questions on quantum mechanics.

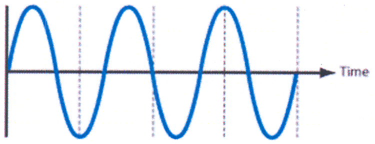
a) Rank the following wavefunctions in order of increasing kinetic energy (KE) where #3 has the highest KE and #1 has the lowest KE.



①



②



③

b) Provide the names for the components of the time independent Schrödinger equation, and provide a brief definition of each component: HΨ =EΨ

H: Hamiltonian: describes forces acting on the system; operator; V+T

Ψ: wave function: describes orbitals as waves; eigenfunction

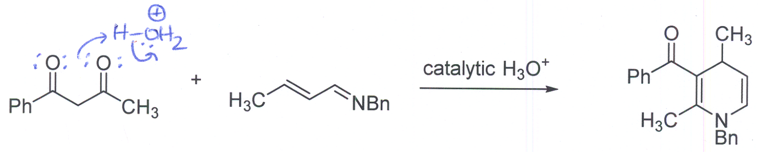
E: energy: of the wave/orbital; eigenvalue

c) What does the minimum of a Morse potential represent? Remember that this minimum is defined by two coordinates and address the significance of both.

r = optimum internuclear distance (i.e. bond length) at which energy is minimized

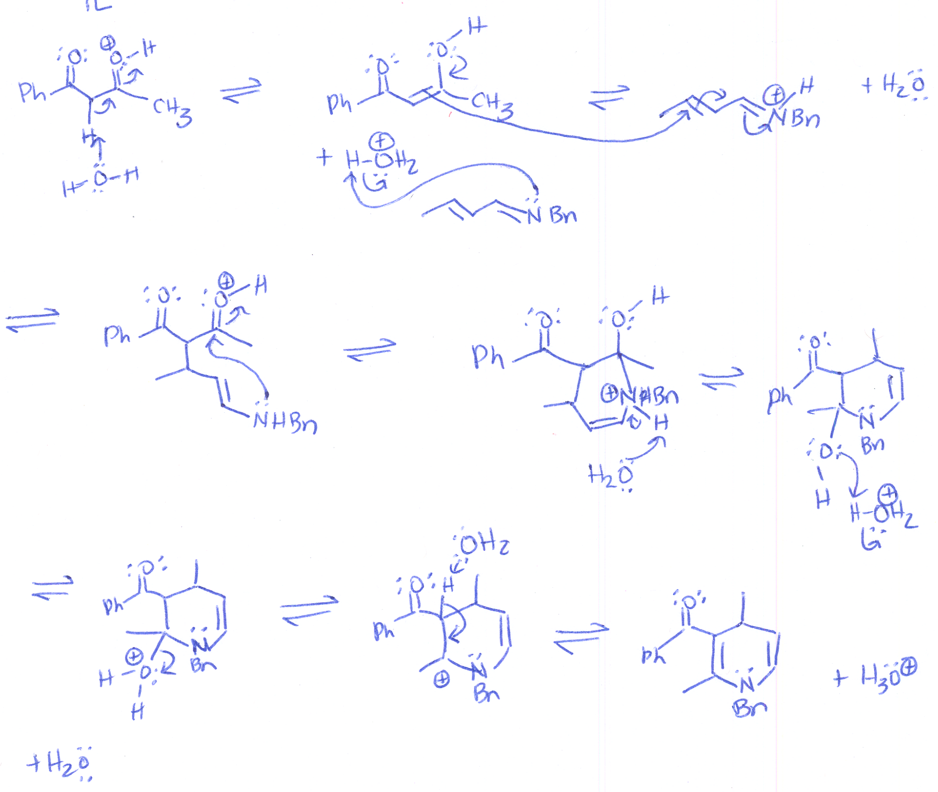
9

~~6.~~ Write the full arrow pushing for the following reaction. Show all intermediates, formal charges, and lone pairs.



8pts

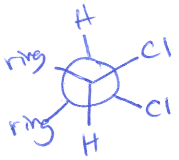
7L



20. (16 pts) Consider trans-1,2-dichlorocyclohexane.

a) Draw Newman projections for each conformation, looking down the bond indicated above with the dotted arrow.

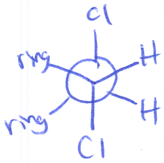
Diequatorial



gauche

syn clinal

Diaxial



1,3-diaxial

anti-periplanar

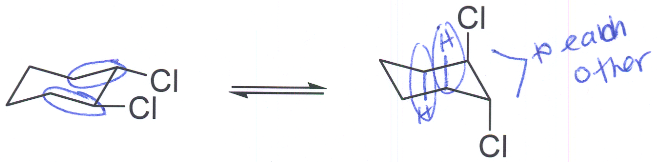
b) Identify strains that are associated with each conformation. List them under your drawings in part a.

c) Using the Klyne-Prelog system, indicate the relationship between the chlorine atoms in each conformation. Do not worry about + or – designations. Write your choices under your drawings in part a.

d) Recall that a weaker bond has electrons in higher energy orbitals. Given that the bond dissociation energy (BDE) for a C-Cl bond is around 84 kcal/mol, and that a C-C bond has a BDE around 90 kcal/mol, which bond has electrons in a higher energy orbital?

C–Cl

e) The two conformers are redrawn for you below. In each drawing, point out the bonds that are anti-periplanar to the C-Cl bonds. If the C-Cl bonds are anti-periplanar to each other, be sure to indicate it.

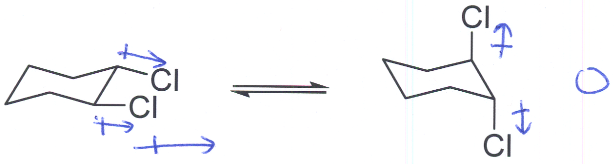


f) In the gas phase, there is a slight preference for the diaxial compound (60:40). Given your answers to parts d and e, rationalize this preference.

donation to σ^* from C-Cl or C-H bonds

anomeric effect

g) Draw the bond dipoles as well as the overall molecular dipole for each conformation.



h) As in the gas phase, there is also a preference for the diaxial conformation in non-polar solvents. However, in polar solvents, the diequatorial conformation dominates. Rationalize the reverse in preference based on the solvent.

non polar solvents don't stabilize dipoles well → diaxial has no net dipole → so is preferred in nonpolar solvents

21. (11 pts) Bond strengths

a) Rank the following C-C bonds in order of increasing bond dissociation energy (BDE), where #3 is the strongest bond and #1 is the weakest bond.

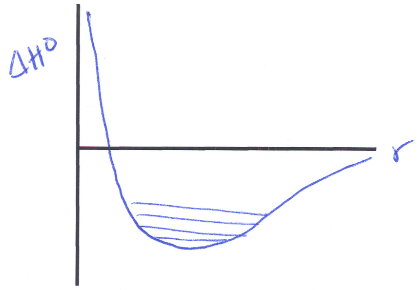
CH_3-CH_3	$H_2C{=}CH_2$	$HC{\equiv}CH$
1	2	3

b) Explain the reasoning for your ranking.

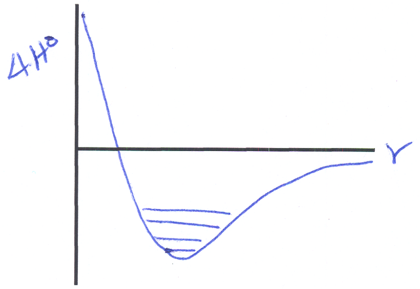
# of bonds, hybridization, s-character

c) Sketch Morse potentials for the C-C bond of each of the three molecules that reflect qualitatively their different relative bond strengths and lengths. Remember to label the axes of your plots. Also, sketch in the first four vibrational energies for each potential.

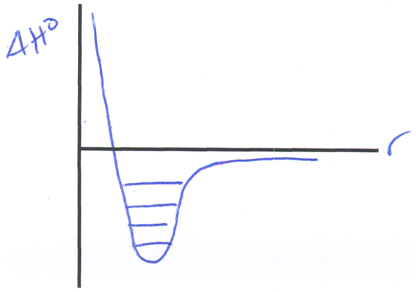
CH_3-CH_3



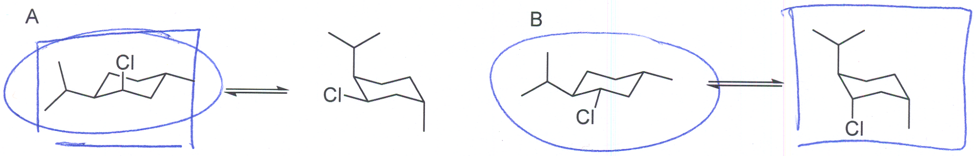
$H_2C{=}CH_2$



$HC{\equiv}CH$



22. (11 pts) Consider the alkyl chlorides A and B below.



a) Circle the conformation of A and of B that each equilibrium favors. Explain your answers.

isopropyl prefers equatorial to minimize 1,3-diaxial strain

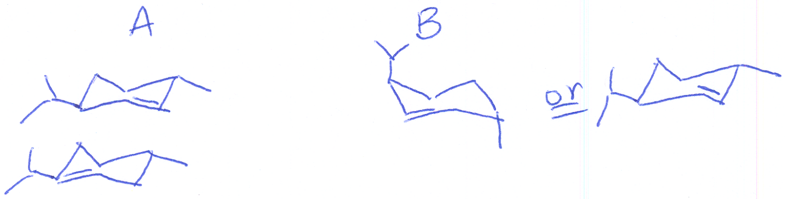
b) Now imagine performing an elimination reaction on alkyl chlorides A and B.

i) Put a square around the conformation of A and of B that can eliminate.

ii) Explain your answers.

C-Cl must be antiperiplanar to C-H

iii) Draw all of the possible products for the two elimination reactions. Be sure to indicate which products arise from A and from B.



iv) The elimination of alkyl chloride B occurs faster than alkyl chloride A. Rationalize this observation. Hint: You should invoke a specific postulate or principle that you have learned in this class.

Curtin-Hammett principle