CEM 351
Final Exam
Friday, December 12, 2003
12:45-2:45 p.m., Room 100, Wonders Hall

Name (print) __________ I. M. Wright
Signature __________________________________________
Student # __________________________
Section Number ________________________

Grade?
☐ 1. (25 pts.) _________
☐ 2. (25 pts.) _________
☐ 3. (25 pts.) _________
☐ 4. (25 pts.) _________
☐ 5. (25 pts.) _________
☐ 6. (25 pts.) _________
☐ 7. (25 pts.) _________
☐ 8. (25 pts.) _________
☐ 9. (25 pts.) _________
☐ 10. (25 pts.) _________

TOTAL (out of 200 pts.) __________

Score __________

Note: Answer any 8 questions for a total score of 200 pts. Be sure to look over all the questions first before beginning the exam, and indicate which eight questions are to be graded by checking the corresponding box.

Recitation | Day and Time | Instructors  | Room
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1. | T 9:10-10:00 a.m. | Yu Zhang | 323
2. | M 10:20-11:10 a.m. | Yu Zhang | 218A
3. | T 10:20-11:10 a.m. | Tulika Datta | 220
4. | Th 10:20-11:10 a.m. | Tulika Datta | 220
5. | T 10:20-11:10 a.m. | Yu Zhang | 323
6. | T 11:30-12:20 p.m. | Tulika Datta | 218B
7. | Th 11:30 - 12:20 | Tulika Datta | 323
8. | M 4:10-5:00 p.m. | Yu Zhang | 136
1. (25 pts) For each of the following pairs of compounds, identify the relationship between molecules (4 pts each). Use the following letter designations and circle your choice at right:

A. Resonance structures
B. Conformational isomers
C. Enantiomers
D. Diastereomers
E. Identical structures
F. Constitutional (framework) isomers
G. None of the above

a.

b.

c.

d.

e.

f. (5 pts) Among the structures shown above, one is meso; find, circle, and clearly mark it as your answer to this question.
2. (25 pts) Quick true/false questions (student written; read carefully here; your classmate(s) are slightly tricky):
   a. (5 pts) A reaction’s rate constant depends on the concentrations of the reactants and products.
      T  F
   
   b. (5 pts) None of the stereoisomers of 2-bromo-4-chloropentane are meso compounds.
      T  F
      \[
      \text{Br} \quad \text{Cl}
      \]
      2-bromo-4-chloropentane

   c. (5 pts) Resonance forms are constantly equilibrating with each other.
      T  F

   d. (5 pts) A Diels-Alder reaction may produce a vinylcyclobutane.
      T  F
      \[
      + \quad \rightarrow
      \]
      vinylcyclobutane

   e. (5 pts) 1,2,4-trioxolane is more stable than 1,2,3-trioxolane.
      T  F
      \[
      \text{O} \quad \text{O}
      \]
      1,2,3-trioxolane
      \[
      \text{O}
      \]
      1,2,4-trioxolane
3. (25 pts) (Student-written question) Consider the following acid reactions:

(a) (4 pts) Draw the two major products of the HCl addition shown below.

(b) (8 pts) Write a mechanism for the HCl addition to form your two products A and B. Check to be sure your compounds actually have the C7H11Cl formula as labeled. Hint: both products arise through the same first step.

(c) (5 pts) Identify which of A or B is the kinetic and which is the thermodynamic product of the HCl addition in part (a). Explain in terms of your mechanism in (b).

(d) (8 pts) The reaction below looks superficially similar to the one above, but ends up in a totally different place. Provide a mechanism for this acid-catalyzed rearrangement and explain the driving force that leads to rearrangement instead of addition.
4. (25 pts) Poor old Igor’s gotten so many things wrong this fall that he feels he must regain his pride or face the holiday season a broken man. He gambles on a synthesis competition with Elvira (who loves him deeply but can’t help the fact that she’s the better lab wizard). They are each to make a hexasubstituted benzene from three chemicals they will pick at random from their supply shelves. Igor picks first but by mistake, pulls out two reagents and (oops) a hot plate. Elvira then draws what look like ideal reagents: a highly activated benzene + a classic aromatic chlorination combination. Igor’s and Elvira’s compounds are shown below.

(a) (4 pts) Elvira combines her reagents and stews them up in the usual solvent (CH$_3$NO$_2$) for such reactions. The reaction goes quickly and she isolates a nice clean product, formula C$_8$H$_7$Cl$_3$O$_2$. Has she made a hexasubstituted benzene yet? Yes No

(b) (6 pts) Draw Elvira’s product and predict how many $^{13}$C NMR lines it should have.

(c) (5 pts) Already feeling beaten, Igor decides to try high-temperature trimerization (shown) of his hexafluoro-2-butyne into an all-fluorinated hexamethyl benzene, using his cyclic diene (aka 3,4,5,6-tetramethylpyranone) as a polar high-boiling solvent:

Unexpectedly, the reaction gets warm by itself when he mixes the ingredients. Even more amazingly, it starts to fizz as he heats it on the hot plate. He isolates a clean compound of formula C$_{12}$H$_{12}$F$_6$, not the C$_{12}$F$_{18}$ he had expected. Igor doesn’t know how he got there, but with Elvira’s patient insights, they work out a possible Diels-Alder-based scheme, and check it by verifying that the gas byproduct is CO$_2$. Draw their Diels-Alder intermediate.

(d) (4 pts) Where’s the CO$_2$ from? Explain with a mechanism in the space above.

(e) (6 pts) Draw Igor’s product. How many $^{13}$C NMR lines does it have? Has he won? Six; YES!
5. (25 pts) (Student-written question) For each of the following reactions, select the necessary reagents from the “lab bench” below to convert 2-methyl-2-butene into the given product. You may simply fill in the boxes with the following letter labels.

(A) O$_3$, then H$_2$O$_2$  
(B) Br$_2$/CH$_3$OH  
(C) H$_2$/Pt  
(D) CF$_3$COOOH  
(E) KMnO$_4$/OH$^-$/H$_2$O  
(F) H$_2$O'/H$_2$O  
(G) HBr  
(H) CH$_3$O'/CH$_2$OH  
(I) Br$_2$  
(J) tBuO-OtBu/HBr  
(K) OsO$_4$, then aqueous Na$_2$SO$_3$

(a) (4 pts)

(b) (4 pts)

(c) (4 pts)

(d) (4 pts)

(e) (4 pts)

(f) (4 pts) Note arrow direction!

(f) (1 pt) Another minor product can arise from the reaction in (f). Please draw it.
6. (25 pts) The compound t-butyl chloride (2-chloro-2-methylpropane) reacts with acetate anion \((\text{CH}_3\text{COO}^-)\) to yield t-butyl acetate and chloride ion. The accepted two-step mechanism for this process is as follows, with the first step slow and the second step fast:

\[
\begin{align*}
\text{Step 1} & : \quad \text{Cl} \quad \rightarrow \quad \text{Cl}^- \\
\text{Step 2} & : \quad \text{O} \quad \text{C} \quad \text{H}_3 \quad \rightarrow \quad \text{O} \quad \text{C} \quad \text{H}_3
\end{align*}
\]

(a) (5 pts) Write the rate law for the reaction. What is the name of this reaction type?

\[
\text{Rate} = k[\text{t-Bu-Cl}]
\]

Reaction type: \(\text{S}_\text{n}^1\)

(b) (10 pts) Assuming the overall reaction is spontaneous (i.e. downhill), in the box provided draw an energy profile for the two-step reaction labeling starting materials, transition states, and any intermediates. Label reactants, products, transition states, the rate-limiting step, and \(\Delta E_{\text{rxn}}\) and \(\Delta E^\ddagger\), as well as the axes of the diagram.

(c) (5 pts) Draw both transition states and describe their structures as precisely as possible using the Hammond postulate.

(d) (5 pts) Draw a detailed structure of the intermediate in this reaction describing its hybridization, shape, chirality (if any), and charge distribution.

\[
\begin{align*}
\text{Intermediate:} & \quad \text{C-Cl bond breaking: Slow, so late TS; C-Cl stretched far} \\
& \quad \text{C-O bond forming Fast, so earlyTS; barrier crossed at long C-O distance}
\end{align*}
\]
7. (25 pts) The general framework structure of steroids (e.g. cholesterol, cortisone, the sex hormones, etc.) is shown below, in both a top view and a side view.

(a) (5 pts) The A and B rings are said to be “fused” (sharing an edge). The B ring is like two substituents on the A ring, and vice versa. Is the A/B ring fusion cis or trans?

(b) (5 pts) “Angular” methyl groups are frequently found at the positions labeled 10 and 13. Draw them in the structure at right and indicate if each is axial or equatorial.

(c) (5 pts) Many steroids have an equatorial OH group at position 3. Draw the OH into the structure at right above and indicate whether the 3-carbon is (R) or (S).

(d) (5 pts) The bridgehead positions are the tertiary carbons at the junctions of two rings. Place hydrogens accurately on the remaining (unmethylated) bridgehead positions.

(e) (5 pts) What is the molecular formula of the steroid you have created, including the methyl and OH groups you have introduced?

\[ \text{Formula} = C_{19}H_{32}O \]

Easy check: \((\text{CHOH})(\text{CH}_3)_2(\text{CH}_2)_{10}(\text{CH})_4(\text{C})_2 = C_{19}H_{32}O\)
8. (25 pts) For each of the following reactions, draw the expected product or products in the box provided. Be careful to think about stereochemistry.

(a) (4 pts)

\[
\text{Ph} \quad \text{H} \quad \text{I} \quad \xrightarrow{\text{CN}^-} \quad \text{R} \quad \text{H} \quad \text{NC} \quad \text{H}
\]

*Show and label stereochemical configurations*

(b) (6 pts)

\[
\text{Ph} \quad \xrightarrow{1) \text{B}_2\text{H}_6} \quad \text{Ph} \quad \xrightarrow{2) \text{H}_2\text{O}_2,\text{HO}^-} \quad \text{R} \quad \text{H} \quad \text{R} \quad \text{S} \quad \text{S}
\]

*2 products; show and label stereochemistry*

(c) (6 pts)

\[
\xrightarrow{1. \text{OsO}_4} \quad \text{R} \quad \text{S} \quad \text{S} \quad \text{R} \quad \text{S}
\]

*2 products; show and label stereochemistry*

(d) (4 pts)

\[
\xrightarrow{\text{Excess HNO}_3/\text{H}_2\text{SO}_4} \quad \text{O}_2\text{N} \quad \text{R} \quad \text{NO}_2
\]

*A famous "high energy material" AKA explosive*

(f) (5 pts) Which of the above reactions gives rise to a diastereomeric mixture?

Reaction (c); these cis/trans isomers are both meso, and hence are non-enantiomeric stereoisomers--diastereomers.
We have looked at the electronic effects of substituents on phenyl ring reactivity toward electrophilic aromatic substitution. We understood them mostly in terms of resonance structures of the intermediates from electrophilic attack. Now let us look at their effects on other characteristics of aromatic systems.

(a) Phenol (hydroxybenzene; old-time name: carbolic acid, used as a disinfectant by Lister, a famous proponent of sterilization of hands and instruments in surgery) is substantially more acidic than simple aliphatic alcohols such as ethanol. Using resonance arguments and precise drawings, rationalize phenol’s greater acidity.

(b) Nitrination deactivates benzene toward electrophilic attack, so nitrobenzene reacts much more slowly than does unsubstituted benzene. On the other hand, nitrination of phenol enhances the acidity of the OH in 4-nitrophenol, as shown above. Explain how these seemingly opposite facts fit together.

(c) Keeping in mind the electronic effects exerted by the nitro and the methoxyl groups on the order of electrophilic aromatic substitution, predict the order of reactivity of the following compounds toward solvolysis ($S_\text{N}1$) in aqueous acetone. Draw the necessary resonance forms to justify your answer.
10. (25 pts) Consider the 8 species shown below:

(a) (8 pts) Which of the above species are expected to be aromatic? Please circle the aromatic structures.

(b) (17 pts) We have learned that simple ethylene is a relatively poor Diels-Alder dienophile:

However, even ethylene reacts rapidly with diene A shown below:

(i) (5 pts) Draw the structure of B.

(ii) (6 pts) Suggest a reason for the enhanced reactivity of A as compared to the 1,2-dimethylenecyclohexane above (hint: think about thermochemistry).

The reaction forms an aromatic compound, so the Diels-Alder has an extra 30 or so kcal/mol of driving force.

(iii) (6 pts) Structure A has two diene fragments (circled). So why is it that B cannot undergo a second Diels-Alder with another mole of ethylene, even under severe forcing conditions? (hint: think about thermochemistry again).

This Diels-Alder would destroy the aromaticity of B, so it is disfavored by the same effect that makes the reaction with A is so good.