Department of Chemistry
Cumulative Examinations

February 23, 2019

You may choose to answer any exam from any area covered in the examination booklet. Each exam may contain multiple parts. You may answer more than one exam but each exam is scored separately and is treated as an individual examination result. Thus, answering parts of two exams with a score of 50% would not yield a 100% grade for this cumulative exam. Instead you would receive 50% on each examination attempted.

This booklet contains five examinations.

1) Analytical Cumulative Examination, Pages 1-2
2) Biochemistry Cumulative Examination, Pages 3-4
3) Inorganic Cumulative Examination, Pages 5-6
4) Organic Cumulative Examination, Page 7
5) Physical Cumulative Examination, Page 8

On your examination booklet:

1) Print your student ID number.
2) Print the Exam Booklet number.
3) Print the question number you are answering.
4) Print the Exam Date.

*Do not write your name anywhere on the examination booklet.* Each exam will be scored anonymously. If you attempt more than one exam, you must use a separate examination booklet for each examination.

When you complete the examination, return the examination and your answer booklet to the proctor. Exam results will be posted on bulletin board #2B on the north side of the hall near BRWN 2124.
In order to be able to utilize mass spectrometry in an intelligent manner, one has to have a basic understanding of the properties of gas-phase ions. In order to demonstrate this, please answer the following questions.

1. Which site in each of the molecules shown below is the most basic site in the gas phase? Justify your choices. 8 pts

2. Which one(s) of the following cations are resonance stabilized? Draw all reasonable resonance structures for the ones you chose. 16 pts

3. Which C-H or N-H bond in each of the following cations has the lowest homolytic dissociation energy? Justify for each case. 8 pts

4. Arrange the following cations in the order from most to least acidic in the gas phase. 10 pts
5. Arrange the following molecules in the order from most to least basic: 10 pts

\[ \text{H}_2 \quad \text{NH}_3 \quad \text{N} \quad \text{OH} \quad \text{NH}_3 \]

6. Which one(s) of the following cations are likely to rearrange? Show the rearrangement product(s). 18 pts

\[ \quad \text{NH}_3 \quad \text{NH}_3 \quad \text{CH}_3 \quad \text{CH}_2 \]

7. Show the mechanism of a favorable unimolecular fragmentation pathway for each of the following cations. 15 pts

\[ \quad \text{NH}_3 \quad \text{CH}_3 \quad \text{CH}_2 \quad \text{NH}_2 \quad \text{H} \]

8. Which cation shown above undergoes McLafferty rearrangement? 4 pts

9. Which cation shown in question 8 undergoes an α-cleavage? 4 pts

10. Which one(s) of the mechanisms shown for question 8 involve a rearrangement reaction and which one(s) involve a direct bond cleavage? Which type of reactions are usually faster? 7 pts
1. (30 points) Below are traces from dynamic light scattering experiments over the same length of time using purified wild-type and mutant kinase protein. The wild-type protein exists primarily as a dimer, whereas the mutant protein is primarily a monomer. Answer the following questions:

\[ \text{A} \quad \text{B} \]

a. Assign the traces to the proteins. (5 points)
b. Explain the basis for your assignments. (10 points)
c. Name another biophysical method that can also distinguish these two proteins. (5 points).
d. Explain how this alternative method can distinguish these two proteins. (10 points)

2. (20 points) Binding affinity.
   a. The dissociation constants (K_D) for many binding interactions are often in the same ballpark with the \textit{in vivo} ligand concentration. Explain these observations. (5 points)
b. Many proteins have multiple binding domains. Explain why multiple binding domains are needed. (5 points)
c. Derive the equation for fractional saturation, f, in terms of [L] and K_D. Given [P], [L] and [P-L]. (10 points)

3. (15 points) Molecular interactions commonly cited can all be considered as special situations of the more fundamental force, electromagnetic force. Please first define and then explain each of the following interactions using this principal.
   a. salt bright (5 points)
b. H-bond (5 points)
c. van del Waals (5 points)

4. (15 points) The energy of a covalent bond as a function of interatomic distance, r, is described by the following equation:
   \[ U(r) = 2000 (r-1.5)^2 \]
   in this equation, energy is expressed in units of kJ⋅mol$^{-1}$ and distance in Å.
   a. What is the equation that describes the force with respect to position? (5 points)
b. What is the force when the interatomic distance is 2 Å? (5 points)
c. At the same value of the interatomic distance, what is the force? (5 points)
5. (10 points) When virologists want to release DNA from the bacterial phage capsids, they add EDTA to the virus samples. Explain the principle of this approach.

6. (10 points) Why do proteins, but not nucleic acids, need to be covered in SDS to estimate the mass by gel electrophoresis?
Inorganic Cumulative Exam  
February 2019

1. In 2016, the Long group described an Fe-based MOF that displays a high-spin to low-spin transition upon CO binding (J. Am. Chem. Soc. 2016, 138, 5594-5602). We will use the following simplified complex to represent the Fe centers in the MOF.

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[Fe(NH3)6(H2O)]^2+
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- Provide a total electron count, Fe oxidation state, and d-electron count for this complex.
- Using the character table, find the reducible and irreducible representations for this complex.
- Sketch each of the ligand-based SALCs and indicate which Fe orbital it can interact with.
- Generate an MO interaction diagram assuming only σ-bonding and fill in electrons.

2. Sketch the d-orbital splitting diagram for the complex, and show how each of the d-orbitals shift in energy upon CO binding. Consider π-bonding interactions. Why does the spin transition occur?

3. The authors use a wide-range of spectroscopic data to determine that a high-spin to low-spin transition takes place with CO binding. For each piece of data, use molecular orbitals, d-orbital splitting, or ligand-field theory to explain why the spin transition causes the observed change.
   - The Fe-N bond lengths contract from 2.1424 Å to 1.9843 Å upon CO binding.
   - The stretching frequency for CO bound to this MOF is 2017 cm\(^{-1}\) while known high-spin Fe complexes have values of 2160-2190 cm\(^{-1}\) and free CO has a value of 2143 cm\(^{-1}\).
   - The magnetic data for three samples shown below shifts systematically with %CO bound.
   - The isomer shift in the Mössbauer spectra shown below drops from 1.2 mm/s (blue) to 0.26 mm/s (red) upon CO binding.

4. Taking into account all of the data presented above, explain why this MOF exhibits good CO adsorption at low pressure (1.45 mmol/g at 100 μbar) as well as ready desorption of CO under mild conditions (vacuum at 150 °C for 5 min).
5. A related Fe-MOF described by the Long group in 2014 (Nature Chem. 2014, 6, 590-595) shows the ability to oxidize alkane C-H bonds using N₂O as the terminal oxidant. **Draw intermediates 1-4 in the catalytic cycle and indicate the Fe oxidation state in each complex.** Note: you may abbreviate the MOF framework as shown in the starting complex.
1. The authors utilize lactone 8 as a key intermediate for the synthesis of (+)-Pillaromycinone. Retrosynthetically, provide the structure of the precursor that leads to 8 and the name of the reaction through which forms 8. (25 pts)

![Chemical structure of 8]

Rxn name

2. Provide a general example of a Staunton-Weinreb Annulation reaction. (15 pts)

3. Provide a plausible mechanism for the conversion of 10 to 11. (25 pts)

![Chemical structures of 10 and 11 with reaction conditions]

4. Provide mechanistic analysis to describe the transformation of 24 to 34. (35 pts)

![Chemical structures of 24 and 34 with reaction conditions]
Physical Chemistry Cum Exam

Computational Chemistry: Simulation Methods, Potential, Free Energy, Solvent Models

You set out to model a molecule of acetone \((\text{CH}_3)_2\text{CO}\) by using different approximations.

1. (5 points) Name the theory you will use that is single-reference post Hartree Fock (HF) “gold standard” scaling \(N^6\) and another theory you could use that scales as \(N^5\), where \(N\) is the number of basis functions.

2. (10 points) If instead of using 6-311G(d) you used 6-311+G(2df,2pd), which level of theory will result in lower energy: energy using HF or the energy from the theories identified in (1)? List the theories in order of decreasing energies and explain why this will be the case?

You decided to choose a force field to model this system “classically,” for computational efficiency by ignoring the electrons in the system. You also further approximated the system by defining a \textit{united atom} type potential energy with \text{CH}_3, C, O as different atom types for acetone.

3. (5 points) What is the dimensionality of the potential energy surface for acetone? Briefly explain your approach.

4. (15 points) Write the potential energy expression clearly explaining all constants and choices that may appear for the isolated acetone molecule.

5. (5 points) What is the dimensionality of the phase space? Write the expression for acetone.

Now you set out to model many acetone molecules in water using classical explicit water models and the same \textit{united atom} representation for acetone.

6. (5 points) Which computational observable would you use to characterize whether acetone molecules are separated or stay together in water?

7. (10 points) The non-bonded forces includes electrostatics and Van der Waals in the “classical” representation of acetone in water. Write the potential energy expression for electrostatics for one molecule of acetone in explicit water. List your parameters and assumptions.

You now decide to run both molecular dynamics and monte carlo simulations for acetone in water system and compare the results using the observable you decided in (6).

8. (10 points) Do you expect to observe similar or different results by molecular dynamics and monte carlo simulations? Why or why not? Explain your result.

Let’s add salt \((\text{Na}^+\text{Cl}^-)\) to this acetone-water mixture and then run the simulations. To characterize the nature of interaction, briefly explain what do you expect by making a sketch of the observable in (6) such that:

9. (10 points) The chloride ions have high affinity to acetone.

10. (10 points) The chloride ions have low affinity to acetone.

You decided to further make the system computationally efficient by modeling solvation of acetone using implicit water solvation models.

11. (5 points) You used GB/SA implicit solvent model for implicit solvent. What is the full form of “GB” and “SA”?

12. (5 points) Which energy components in the Hamiltonian does GB and SA correct for implicit solvation effect?

13. (5 points) Write the components of free energy of solvation. Name a method to calculate change in free energy will you use to convert acetone to thioacetone \((\text{CH}_3)_2\text{CS}\)?