Chapter 10. Integrated Molecular Modeling, Synthesis, and Characterization Experiments for the Undergraduate Inorganic Chemistry Laboratory. Chemical Education Experimental

Molecular Modeling.

The molecular modeling package used was the CAChe Server/Satellite 3.0-3.1 software from Oxford Molecular Group. This client-server software uses PC compatible computers as client machines for drawing structures and displaying experimental results. All calculations (geometry optimization, molecular orbital calculations, etc.) are performed on a central server (Silicon Graphics, Indigo or Octane model, 270 MHz). Geometry optimization of the molecules was performed with the CAChe Molecular Mechanics routine using either augmented MM1 parameters, or Allinger's standard MM2 force field.[103] HOMO and LUMO diagrams and energies, as well as partial charges, were calculated at the ZINDO (INDO/1) and Extended Huckel levels. Electronic absorption spectra were calculated at the ZINDO (INDO/1) level, using current geometry.

The CAChe Server/Satellite system has two ZINDO engines: small (140 atoms and 490 basis function maximum) and large (200 atoms and 700 basis function maximum).[103] The appropriate engine will automatically be selected by the software. ZINDO contains the theoretical (INDO/1) parameters for the following elements: H, Li - F, Na - Cl, K - As, Br, Y - Cd, and I.[103] ZINDO contains the spectroscopic parameters (INDO/1) for the following elements: H, Li, B - F, P, S, Sc - Zn.[103]
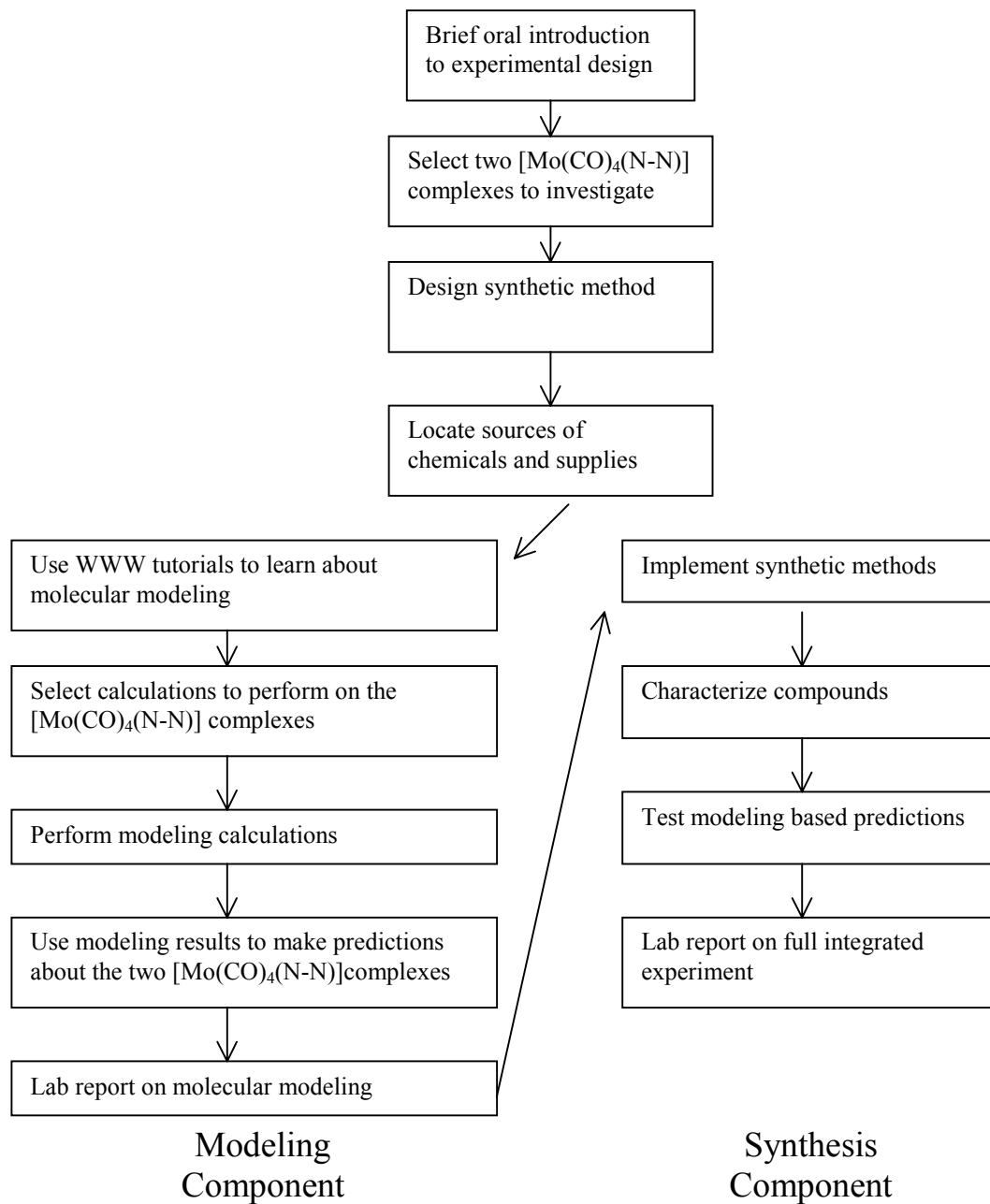
Integrated Laboratory Experiments.
[Mo(CO)$_4$(N-N)]
This experiment utilizes two [Mo(CO)$_4$(N-N)] systems, where N-N is a bidentate nitrogen donor ligand. It is completed in two parts, with basic goals for each section. Its first goal is to model the two [Mo(CO)$_4$(N-N)] systems selected and make predictions as to the physical data based on the modeling; its second goal is to synthesize and characterize both complexes and analyze the predictions previously made. A schematic outlining the design of the integrated molecular modeling, synthesis, and characterization

laboratory experiment is found in Scheme 10.1. The integrated experiment as it is
presented in the inorganic chemistry laboratory manual is found in Figure 10.1.

Scheme 10.1. Design of the Integrated Molecular Modeling, Synthesis, and
Characterization Experiments for Inorganic Laboratory.

Modeling
Component

Synthesis
Component

Scheme 10.2. The Integrated Molecular Modeling, Synthesis, and Characterization Experiment, as Presented in the Laboratory Manual for the Inorganic Chemistry Laboratory (Chemistry 4414).[136,137]

Experiment 3A. Molecular Modeling of Organometallic Molybdenum Compounds

The goal of this experiment is to model a series of organometallic complexes that have one ligand that is varied and to see how this variation of the ligand changes the properties of the complexes as predicted by molecular modeling. You will use these molecular modeling results to make some predictions about the properties of these complexes. You will then prepare the complexes you modeled (Experiment 3B) and see how well your predictions of chemical properties obtained from the modeling experiments fit the observed properties. The CAChe program allows you to calculate a number of properties of your complexes. These include optimized geometry with bond distances, electron density, HOMO-5 to LUMO+4, electrostatic potential, electrophilic susceptibility, nucleophilic susceptibility, etc... You should pick a property that you think you can correlate to an experimentally observable quantity that can be measured on the department's equipment.

[Mo(CO)$_4$(NN)] with two different NN ligands.

In this experiment you will model two different molybdenum complexes that vary in the particular nitrogen donor ligands which are utilized. The NN ligands would commonly be a bidentate diimine ligand like 2,2-bipyridine, 1,10-phenanthroline or a variety of substituted analogs. Your laboratory report needs to address how this modification of the ligands is predicted to change the properties of your complexes. You need to use these modeling results to make predictions about the **relative** physical properties of the two systems you modeled. You don't have to try to make absolute predictions of properties. Properties that you might try to correlate to modeling results are IR spectroscopy, UV-vis spectroscopy, electrochemistry, NMR spectroscopy, etc..The ligands you select for the modeling studies will be the ones used in the synthesis part of this experiment (Experiment 3B) so make sure to consider their availability in your ligand selection process. The ligands you plan to use need to be approved by your TA prior to beginning Exp. 3A.

To begin this experiment you need to go to the inorganic laboratory in Davidson 128 and open Netscape. Using this browser open the Chem 4414 homepage (http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/4414.html). Follow the links indicated for experiment 3A, instructions for the molecular modeling experiment. Your experiment will begin with the use of some tutorials for instruction on how to use the CAChe molecular modeling package. After you have completed the CAChe tutorials, you are ready to begin your own modeling experiments. One word

of caution for these molybdenum complexes, DO NOT use any energy minimization other than MM. The others do not work properly with these Mo complexes and will give results that are obviously incorrect! If you need assistance, contact your TA or Prof. Brewer. You must decide what type of properties you would like to model (Experiment 3A) and what physical properties you will be able to measure (Experiment 3B) to correlate to your modeling results. Some types of modeling experiments you can perform using the CAChe system on these Mo complexes include:

1) Molecular Mechanics Energy Minimized Structure to compute bond angles and bond distances.
2) Huckel MOs to view shapes and localization of orbitals as well as relative energies of MOs and HOMO - LUMO energy gap.
3) ZINDO MOs to view shapes and localization of orbitals as well as relative energies of the MOs and HOMO - LUMO energy gap.
4) Huckel MOs to obtain partial charges on the atoms.
5) ZINDO MOs to obtain partial charges on the atoms.
6) Electron Density Isosurface using Huckel MOs.
7) Electron Density Isosurface using ZINDO MOs.
8) Any other modeling result you think will correlate with an experimentally observable quantity.

Some types of properties of your complexes that you might attempt to correlate to molecular modeling results include:

1) IR spectroscopy, particularly C-O stretching frequency
2) Electrochemically measured reduction potential
3) Electrochemically measured oxidation potential
4) Electrochemically measured HOMO - LUMO gap
5) Electronic absorption spectroscopy, particularly the energy of the lowest lying electronic transition.
6) NMR, chemical shifts of selected nuclei.
7) Any other property you can measure that you think will correlate with an experimentally observable quantity.

Tips for getting your modeling results into your lab reports!
When you have your modeling results displayed in the CAChe program you can hold down the alt button and depress the print screen button. This will copy your modeling results onto the clipboard. Then open up the lview program. Use the Edit menu and select paste. This will paste your screen capture into lview. You can then use your cursor to make a box around the part of your results you would like to keep and use the Edit menu and the crop command to get rid of the other parts of the screen capture. Now you can save your results as a graphics file on a floppy diskette or you can copy your results back onto the clipboard and then paste them directly into

a word document or a PowerPoint presentation. Those can also be saved on a floppy for you to take with you and use in the preparation of your lab report. You can also print directly from the CAChe program but using lview and Word or PowerPoint allows you to get your results in a format that will fit on a floppy diskette.

Experiment 3A and 3B are part of an integrated molecular modeling, synthesis and characterization laboratory designed to teach molecular modeling concepts in an integrated laboratory setting. This approach uses the internet and distributed learning to assist in the instruction of molecular modeling concepts and software usage. The design of the experiment allows for student input in the selection of the compounds to model and prepare and the nature of the molecular modeling performed. Students also select the physical property they want to make predictions concerning as a result of their molecular modeling results. The experimental design for Experiments 3A and 3B is as follows:

1) The students select two $[Mo(CO)_4(NN)]$ complexes that vary the NN ligand (since you will have to prepare these complexes later please check with your TA regarding the suitability of the NN ligands and your proposed synthetic methods).
2) The WWW tutorials are used to assist in learning the use of the CAChe molecular modeling package. (The tutorials are found by following the links to the molecular modeling experiment on the course home page http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/4414.html.
3) The students select the type of modeling exercises they would like to perform on their two $[Mo(CO)_4(NN)]$ complexes and they carry out these exercises.
4) The students output and view their molecular modeling results and use these to make a prediction regarding some measurable physical property of the two $[Mo(CO)_4(NN)]$ complexes they selected.
5) The students use the synthetic method they designed in consultation with their TA to prepare the two $[Mo(CO)_4(NN)]$ complexes.
6) The students characterize the two $[Mo(CO)_4(NN)]$ complexes both to prove they have successfully prepared the proposed complexes and to measure the physical property about which they made a prediction from their molecular modeling results.
7) The students compare the predictions they made from the molecular modeling exercise to that they observe in the characterization of their complexes and analyze the correlation.

Experiment 3B. Preparation of Organometallic Molybdenum Compounds

The goal of this experiment is to prepare a series of organometallic complexes which have one ligand that is varied and to see how this variation of the ligand

changes the properties of the complexes you prepare. These are the same two complexes you modeled in Experiment 3A. You will need to prepare and fully characterize your complexes. In your selection of ligands, you may find that you would like to utilize a ligand that is not available in the laboratory. If this occurs, consult with your TA about the procedure to purchase your desired ligand. This experiment couples directly to Experiment 3A. Molecular Modeling of Organometallic Molybdenum Complexes.

[Mo(CO)$_4$(NN)] with two different NN ligands.

In this experiment you will prepare two different molybdenum complexes which vary in the particular nitrogen donor ligands which are utilized. The NN ligands would commonly be a bidentate diimine ligand like 2,2-bipyridine, 1,10-phenanthroline or a variety of substituted analogs. Once you have prepared these complexes they need to be FULLY characterized to probe how changing the NN ligand changes the properties of the complexes prepared. Your laboratory report needs to address how this synthetic modification changes the properties of your complexes. Your report should also address the predictions you made from the molecular modeling experiment, Experiment 3A. You need to present the major conclusions of your molecular modeling experiment highlighting the predictions you made concerning physical properties of your two [Mo(CO)$_4$(NN)] complexes. You should then clearly indicate how you measured these properties and whether your predictions were correct or not. You should then analyze the correlation between the predicted properties (from molecular modeling) and the measured properties (from the preparation and characterization of your complexes).

Following are a couple of experimental procedures which researchers have used in the past to prepare complexes of the type described above. You will need to go to the library and research your particular systems in order to develop an appropriate synthetic method. You must discuss the details of your synthetic method and all relevant safety precautions with your TA prior to beginning your experimental work.

Experiment 3A and 3B are part of an integrated molecular modeling, synthesis and characterization laboratory designed to teach molecular modeling concepts in an integrated laboratory setting. This approach uses the internet and distributed learning to assist in the instruction of molecular modeling concepts and software usage. The design of the experiment allows for student input in the selection of the compounds to model and prepare and the nature of the molecular modeling performed. Students also select the physical property they want to make predictions concerning as a result of their molecular modeling results. The experimental design for Experiments 3A and 3B is as follows:

1) The students select two [Mo(CO)$_4$(NN)] complexes that vary the NN ligand (since you will have to prepare these complexes later please check with your TA regarding the suitability of the NN ligands and your proposed synthetic methods).

2) The WWW tutorials are used to assist in learning the use of the CAChe molecular modeling package. (The tutorials are found by following the links to the molecular modeling experiment on the course home page http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/4414/html).
3) The students select the type of modeling exercises they would like to perform on their two [Mo(CO)$_4$(NN)] complexes and they carry out these exercises.
4) The students output and view their molecular modeling results and use these to make a prediction regarding some measurable physical property of the two [Mo(CO)$_4$(NN)] complexes they selected.
5) The students use the synthetic method they designed in consultation with their TA to prepare the two [Mo(CO)$_4$(NN)] complexes.
6) The students characterize the two [Mo(CO)$_4$(NN)] complexes both to prove they have successfully prepared the proposed complexes and to measure the physical property about which they made a prediction from their molecular modeling results.
7) The students compare the predictions they made from the molecular modeling exercise to that they observe in the characterization of their complexes and analyze the correlation.

Exploring the Properties of [Mo(CO)$_4$(N-N)] Complexes.

Before this integrated laboratory experiment was incorporated into the undergraduate curriculum, a series of [Mo(CO)$_4$(N-N)] complexes was synthesized, characterized, and modeled using the CAChe software, Table 6.1 (page 61). Correlations between the physical and computational data was tested.

Correlation with Molecular Modeling.

Geometry optimizations, energy minimized structures for each system, were found using molecular mechanics routines (MM2). Extended Huckel and ZINDO calculations were both used to calculate molecular orbitals, partial charges, and calculated bond orders. Electronic absorption spectra calculations were performed for each [Mo(CO)$_4$(N-N)] using the ZINDO CI algorithm at current geometry.

WWW Assisted Instruction on Molecular Modeling Package.

To facilitate the students learning of the CAChe molecular modeling software, a series of WWW-based tutorials were developed.[135] The tutorial series has since been expanded to include sets for general use[146], use in the organic course[147], as well as for the

inorganic laboratory.[135] The tutorials for use in the inorganic laboratory were developed so that the students could learn about the molecular modeling techniques in a fairly independent fashion, in or outside of class time. This helps to facilitate the self-paced aspect of this experiment.

The tutorials are broken into sections, each covering a different molecular modeling topic.[136] This was done to keep topics as discreet and simple as possible, and so that one may return to a section for review without having to go through all of the other sections. The topics (sections) included in the tutorials for inorganic laboratory include:

1. **Overview of the CAChe screen.** This section provides a clickable image of the CAChe screen, giving an overview of the features available in the software. (http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/CAChe/screen/new_screen1.html)

2. **Building a simple ligand.** 2,2'-bipyridine and 4-vinyl-4'-methyl-2,2'-bipyridine ligands are built, teaching the modeling of organic compounds necessary in inorganic chemistry. (http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/CAChe/ligand/ligand1.html)

3. **Building a metal complex.** Teaches students to expand the information learned in (2.) to build simple metal complexes. (http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/CAChe/metal/metal1.html)

4. **Molecular mechanics energy minimization.** This tutorial covers the application of CAChe molecular mechanics program to provide an energy-minimized structure of the metal complex built in tutorial (3.) (http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/CAChe/mech/mmech1.html)

5. **Extended Huckel calculation.** Uses the semi-empirical quantum mechanics calculation to find molecular orbitals for the metal complex built in (3.) (http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/CAChe/huck/mhuck2.html)

6. **ZINDO calculation.** Uses the semi-empirical quantum mechanics calculation to find molecular orbitals for the metal complex built in (3.) (http://www.chem.vt.edu/chem-dept/brewer/chem-ed/4414/CAChe/zindo/mzindo2.html)

The tutorials designed for general use contain additional tutorials which may also be completed by the inorganic laboratory students. These include exercises on mopac, UV-vis, and IR calculations, and conformational analysis. Each of these tutorials contains links to the NIH molecular modeling website. This is an important reference, as it contains information on molecular modeling theory as well as links to other valuable resources. The NIH site also hotlinks to our general use tutorials making them widely available to CAChe users.

Evaluation of Project.

Upon the completion of full integration of this experiment into the inorganic laboratory, it was necessary that a project evaluation be completed.[133,134] Dr. Darrel Clowes in the Education Department at Virginia Tech helped with the ideology and design of this method of evaluation. This evaluation was done in both spring 1998 and 1999 in a comprehensive, standardized interview format. The same interview was given to each student both semesters. This style was used in an effort to minimize researcher and student bias, and to allow for the maximum amount of student input and comment.[129,133] Upon the completion of the interviews, they were transcribed and "rendered". This involved reviewing the set of interviews multiple times in an effort to extract themes.[129,130,133]

Each student was interviewed privately. They were first given a consent form indicating that the interview was for the purpose of evaluating the program, shown in Scheme 10.3. The individual results of the interviews were confidential and would have no affect on the experiment or course grade.

Also of interest were student-suggested modifications of this experimental design that could make this a more effective teaching tool. Students were informed of our interests and were asked to be detailed and honest in their evaluation of this project. The interview questions can be found in Scheme 10.4.

Several issues were addressed in our evaluation. These included:
A. the effectiveness of our WWW tutorial approach to teaching molecular modeling with the CAChe system;

B. the success of the integrated experimental design in enhancing student understanding of molecular modeling results, orbital properties of inorganic systems, and characterization data;

C. the usefulness of distributed learning for incorporating molecular modeling into our curriculum; and

D. the integrated experimental design.

Scheme 10.3. Student Release Form.

> I,   (Student Name) give Elizabeth R. Bullock permission to interview me regarding the integrated molecular modeling, synthesis, and characterization experiments that I completed in the Inorganic Laboratory course (chemistry 4414). I understand that the content of this interview will remain anonymous, and that this interviews will in no way affect my course grade. The result of these interviews may be used (anonymously) for future work, and or, publications on this topic.
>
> Student Name   Student Signature
> Elizabeth R. Bullock   ER Bullock's Signature
> Date

Scheme 10.4. Student Interview Questions.

1. Name
2. Age
3. Expected degree—anticipated graduation date
4. Career goals
5. Class mandatory or elective
6. WWW tutorials: Were these helpful? Did they provide adequate information to effectively use CAChe?
7. What changes would you make to the tutorials to make them more helpful?
8. What, if any other instructional methods would have aided in learning to use CAChe?
9. The goal of this project was to introduce molecular modeling to students because it is becoming widespread in chemical research: Do you ever anticipate using molecular modeling in the future?   Have you found your molecular modeling experience to be informative/helpful?

10. The calculations done with CAChe correlate with certain characterizational data obtained from the synthesis and characterization aspect of the laboratory. Do you feel that your understanding of the physical/characterization data was influenced by having completed the molecular modeling? Why or why not?

11. Which compounds were synthesized? Do you feel that the compounds selected for this study were appropriate for this integrated laboratory experiment? Do you have any suggestions for new experiments?

12. How were your compounds synthesized: photochemically or thermally? Your experience of these?

13. Was the background learned from previous classes sufficient, or should this experiment be carried out at a different point in the semester?

14. How much would your understanding of the molecular modeling/synthesis/characterization experiment has been improved by correlation with the class schedule?

15. Where were the problems in understanding the correlations between molecular modeling and characterization? Where did you go for help with this?

16. What could be added to the tutorial or lab manual to clarify problems/questions?

17. How accessible was help in understanding these questions?

Upon examination of the sample statistics, the sets of transcribed interviews are rendered. This is done to extract themes prevalent throughout the sample. Rendering involves an in depth review of responses to interview questions, repeated multiple times. Themes found throughout are examined to further ensure that they accurately reflect the statements made by the students.