The Implementation of a Spartan Model's Effect on Students' Overall Understanding of Esterification Reactions

Honors Thesis

Florida Southern College

by
Korinne Mills

Abstract

Organic Chemistry students often struggle with using information provided to them to extend to new situations. Inquiry-based labs and assignments have shown to improve students' ability to extend their knowledge to new situations. For example, rather than confirming what students already know, inquiry-based labs can help students internalize the concepts. This may help students, for example, rationalizing how substituents may impact a reaction. Students at Florida Southern College have an inquiry-based lab on greener esterification that explores the effect of substituents on greener esterification reactions, which requires students understand and apply many different conceptual phenomenon. Though students can recognize there is a pattern in the data, they struggle with justifying their observations. An activity using Spartan, a computational software that produces calculated visualizations and numerical values for molecules and reactions, was introduced prior to the students completing the inquiry-based lab and writing their lab report. Its effect on students' understanding of the lab was then determined through comparing students' lab reports from this year to students' lab reports from previous semesters who did not complete the model-based activity. Students' learning progression throughout Organic Chemistry I and II was followed to determine the effect of the model-based activity on students' understanding. Students' foundational understanding of electron density was determined at the beginning Organic Chemistry I and followed as students learned about electrophilicity and the reactivity of benzene ring derivatives via questions on in class quizzes. From the analysis of the open-ended questions on the in-class quizzes emerging misconceptions were also determined.

Introduction

In 2016, approximately 22,000 undergraduate students received a Bachelor of Science Degree in Chemistry in the United States.[1] Yet, as many degrees and pre-professional requirements require extensive coursework in chemistry, students who received a degree in Chemistry comprised only a small percentage of undergraduate students who took an undergraduate chemistry course.[2] Many students find these chemistry courses challenging, specifically citing Organic Chemistry as one of their most challenging courses as it relies on students' ability to understand and interpret the relationship between molecules, their interactions and reactions. This understanding is fundamental to the course's laboratory component, which supplements most chemistry lectures and assesses if students can apply the lecture material, while also supplementing the skills students will need in their future research or careers.

To aid in students' ability to understand the course's challenging material, models are frequently utilized to visually represent and connect a theory in chemistry to real life. Since chemistry concepts are foundational to the microscopic, macroscopic and symbolic nature of scientific phenomenon in chemical and biological systems, it is important for students to make these connections. Models in chemistry span from tangible models such as model kits to computational visualizations, such as computer-generated images and electrostatic maps, reactions and mechanisms arrows, and calculations, such as those used in thermodynamics and kinetics.

Previous studies have shown that students' scores improved following the use of models on post-evaluations. This improvement was especially significant for students who scored below average on their ability to apply information, visuospatial skills and comprehension.[3] Students' improvement on post-evaluations was shown with a variety of models, each that emphasized different concepts and relationships.[4] Understanding the relationship between the phenomena, while easy for instructors and experts, is more difficult for students. Models provide students a resource to aid students by decreasing the cognition required to transition the chemistry phenomena. These models include virtual and traditional, concrete, “hands on” models. Virtual models, including computer simulations, can be further subdivided into stereo, providing a three-dimensional representation, and interface models, providing an interactive representation. When the two models were compared, the stereo model was more effective in increasing students’ understanding of the phenomenon.[5,6]

One stereo model includes Spartan, a chemical software, which is designed to perform extensive calculations for computational and experimental chemists, who may have little experience.[7] The Spartan chemical modeling software has been previously used in published activities, including the utilization of comparing electron density maps in a pre-lab assignment for a thin layer chromatography (TLC) lab, providing a guideline on how other Organic Chemistry labs have utilized the software.[8] The software allows for experimental calculations and will display maps of the molecule’s environment. Therefore, students can utilize this software to complete activities, such as comparing benzene derivatives' electron environments through electrostatic potential maps and compare molecular orbitals energies and local ionization potential maps. Electrostatic static potential maps are computer generated images that display predicted electron densities based on calculated or semi empirical data. The red or warmer colors regions represents high electron density to lower electron density as shown in Figure 1.

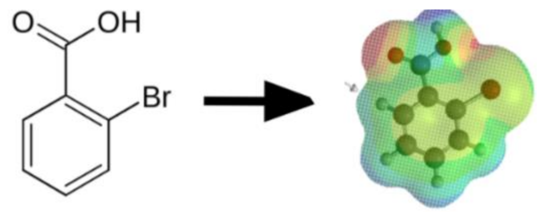
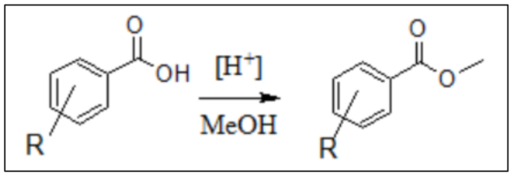


Figure 1: Electrostatic potential map of 2-bromobenzoic acid made using the Spartan software.

This comparison provides students with a basis of the foundational information for benzene derivatives' bonding and chemical reactivity based on the apparent charge distribution. From gathering this data, students can then draw conclusions on the electrophilic characteristics of the molecules tested in an accompanying inquiry-based lab experiment. Further, based on students' predictions of such reactions, they should be able determine their product. Their product can then be drawn on Spartan, and the NMR and IR spectra can be obtained. This allows students to compare their spectra to the known, and determine if their sample was the predicted product, other products, or contained impurities.[9] This ability is helpful in an inquiry-based lab, as the structure of an inquiry-based lab is designed to task with creating their own procedure based on provided background literature, similar experiments, and material from lecture and predict their results. This structure has been shown to be more effective in increasing students' understanding of the information, increasing their perceived ability to think critically, and increasing their interest in the experiment.[10,11,12]

Often the impact of substituents is not discussed in detail in Organic Chemistry. However, examining the impact of substituents on a reaction requires prior knowledge from as far as General Chemistry. In Organic Chemistry II, students examine the mechanism of esterification reactions and conduct these reactions in an inquiry-based lab (Scheme 1). To aid students' critical thinking ability to extend this knowledge to effects of substituents on a reaction, various models, such as Spartan can help students make sense of observations.



Scheme 1: Esterification of Benzoic Acid Derivatives with Methanol.

Computational data such as the lowest unoccupied molecular orbital (LUMO) energy values implies information on the electrophilicity of the molecule, and in this case, can also imply information on the electrophilicity of the carbonyl carbon, while the electrostatic potential maps provide a visual overall representation of the electron density on the molecules. Lower LUMO values imply increased electrophilicity, hence, increased reactivity. Table 1 shows LUMO energy values for various benzoic acid derivatives. This data shows that electron withdrawing groups, such as a nitro group, have low LUMO values and electron donating groups, such as amino groups, have higher LUMO values. It should be predicted that this table mimic students' data so they can try to justify their results. However, it should be noted that this data does not include experimental errors, issues with stirring, consistency in heating and so on.

Compound	**E LUMO, eV**
4-nitrobenzoic acid	0.51
benzoic acid	2.36
4-bromobenzoic acid	2.18
4-methoxybenzoic acid	2.96
4-Aminobenzoic acid	3.19
4-hydroxybenzoic acid	2.74
benzoyl chloride	1.78

Table 1: LUMO energy values calculated by Spartan Student V8 using Hacktree-Fock (semi-empirical) Method.

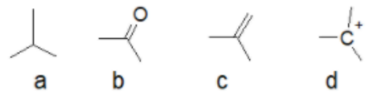
Students cannot simply make these connections without connecting prior knowledge between exposure to Spartan and this lab. Therefore, this chemistry education research project evaluates students' understanding over time and the use of Spartan in students' culmination of their knowledge in laboratory reports on the substituent effects in the esterification. Students' learning outcomes from the activity, inquiry-based lab, and overall phenomenon will be measured throughout two semesters of Organic Chemistry.

Methodology

Prior to any assessments, the project was reviewed by Florida Southern College's Human Subjects Institutional Review Board and granted a one calendar year approval (FASC IRB 202021-027). The assignments given to students taking Organic Chemistry in Fall 2020 and Organic Chemistry II in Spring 2021 throughout the two semesters were implemented in accordance with the course's usual assignments. In the first semester, these assessments tracked students' progression of understanding from their foundational understanding of electron density to their understanding of the reactivity of benzene ring derivatives.

The first assessment was two questions incorporated on an in-class quiz in the first month of Organic Chemistry I. The first question asked students to rank three molecules' central carbons based on the electron composition of three molecules and explain their answer. The second question then asked students to match those molecules to their respective electrostatic maps based on their electron density (Appendix 1).

Rank the electrophilicity of the center carbons from MOST to LEAST electrophilic of the below molecules and explain your answer.



Sample Question 1: The first question on the students' first in class quiz given in the first month of Organic Chemistry I and at the start of Organic Chemistry II.

The second assessment, three questions on an in-class quiz with similar structure, was given to students after they had learned about nucleophilicity and electrophilicity. The first question asked students to rank the electrophilicity of the molecules' center carbon and explain their answer. The second question, a true or false question, asked students if the LUMO value provides information about the electrophilicity of a molecule, and the third question asked students which molecule they expected to have the lowest LUMO energy and to explain their answer (Appendix 2). The first two question sets were given again on one in-class assessment at the start of Organic Chemistry II to track students' progression.

The third set of questions further assessed students' understanding by including a comparative and justification question on an in-class quiz in Organic Chemistry II. The quiz was given at the beginning of the semester following students' introduction to esterification reactions and substituents' effect on reactivity from the lecture component of the course and from background knowledge from their textbook, *Organic Chemistry* by David Klein. The first question asked students which molecule would more readily react with a nucleophile and to explain their answer. The second question asked how adding a bromine group to the para position on the ring would affect the reaction and to explain their answer using their knowledge of electrophilic properties and substituents effects previously discussed (Appendix 3).

The Spartan activity and introduction to the inquiry-based lab were then provided to students. The learning objectives were clearly defined detailing the specific material students should be able to understand and apply (Appendix 4). Students were then asked to complete the pre-lab Spartan activity to compare benzene derivatives' electron environments on an electrostatic potential map, molecular orbitals energies, and local ionization potential maps for the benzene derivatives (Appendix 5). Following the Spartan activity, students were tasked with completing the pre-lab questions and to make predictions on the electrophilic characteristics of the molecules tested in the inquiry-based lab (Appendix 6). Students then completed the inquiry-based lab using the principles of green chemistry in small student groups. The lab, created by Dr. Bromfield Lee, focused on the effect of substituents on a greener esterification reaction (Appendix 7).

Following completion of the inquiry-based lab and Spartan activity, students were given questions to answer in their electronic lab notebook, which asked them questions about predicting and explaining possible reactivities, trends, and the electrostatic, ionization and LUMO map properties (Appendix 8) and were tasked with writing a lab report, as directed in their lab handout (Appendix 7). The lab report was written in the student lab groups, comprised of two to three students.

The open-ended questions on the quizzes were then assessed and analyzed for the correct answer, including the correct ranking of molecules when required, and the students' correct reasoning/justification in their explanations. The justifications for the correct answers were scored according to the Sandoval Framework, which focuses on three aspects of their answer, elements (necessary for the argument), articulations (support), and warrants (valid evidence) on a 0-, 1- and 2-point scale (Table 2).[13] The students' justifications were then further analyzed to determine if there were any emergent patterns in students' misconceptions, and students' progression was measured over the course of the quizzes.

Score/Level	Criteria
0	Student's answer was not correct nor was their reasoning in their explanation (incorrect or irrelevant explanation).
1	Student's answer incorporated aspects of the correct response but did not have full reasoning, enough to justify and support their answer (partial explanation).
2	Student's answer clearly, and correctly related their reasoning and argument with enough support to justify their answer (full and correct explanation).

Table 2: The criteria for the Sandoval Framework scores, 0, 1, or 2, given to students' answers based on their level of reasoning and correct justification in their answer answers.[13]

The students' lab reports were also scored based on 0-, 1-, and 2-point scale (Table 2), and further analyzed for interrelated concepts. Students were encouraged to use evidential support in their answer, and the report was given a cohesive score based on a scale of 0 to 1 depending on how fluid their argument was. This was determined by how well students mapped the elements of their argument.

All of the scores from students' justifications on the open-ended questions and the lab reports were scored by two independent graders, and interrater reliability was determined using Cohen's kappa to ensure there was at least an 85% agreeance. The scores of previous student's lab reports and the students, who completed the activity, lab reports, for students completing the activity were utilized to determine the effect of the activity on students' learning outcomes and the students' scores were compared to previous years students' scores who completed the Spartan activity to determine its effect.

Results & Discussion

On the first set of questions on the first quiz (Appendix 1), 32% of students (n=47) correctly ranked the carbon from greatest to least electron density, while 38% of students ranked the electron density from least to greatest. In their explanations, 30% of students were level 0 answers, 45% were level 1 answers and 25% were level 2 answers. On the second question, 28% of students (n=45) ranked the electron density from least to greatest electron density. Of the incorrect ordering for the molecules' electrostatic maps, most students chose the incorrect electrostatic map for chloroform. In their explanations, 24% of students were level 0 answers, 42% were level 1 answers and 33% were level 2 answers. The interrater reliability between the two independent graders was 91% with a Cohen's k value of 0.80.

Score/Level	Explanations
0	Cl is larger than O, and O is larger than C
1	CH3OH is the most electron dense because it has hydrogen bonding, which contains extremely electronegative atoms. CHCl3 is the next dense molecule because it has electronegative atoms, but two of the Cl atoms cancel each other out, leaving only the pull of one Cl. Finally, CH4 is the least electron dense because it has low electronegative atoms and the only force acting is London dispersion forces.
2	Chlorine is pretty electronegative, so having three chlorines on the central carbon atom will make the electron density the highest. Then having an alcohol group attached to the carbon will make CH3OH second most electronegative because the oxygen will have a slightly negative charge. CH4 will have the least electron density because there's really nothing with any sort of charge on it to make the electrons flow in any sort of direction.

Table 3: Sample responses for the first question on the first quiz (Sample Question 1) which were scored on the scale of 0, 1, and 2 based on the rubric (Table 2).

On the second quiz in the first semester (Appendix 2), 59% of students (n=35) correctly ranked the electrophilicity of the center carbons from most to least. In their explanations, 12% of students were level 0 answers, 65% were level 1 answers, and 23% were level 2 answers. 91% of students agreed the LUMO value tells you some information about the electrophilicity of a molecule, and 55% of students selected the correct molecule expected to have the lowest LUMO energy. In their explanations, 23% of students were level 0 explanations, 37% were level 1 explanations, and 40% were level 2 explanations. The interrater reliability was 91% with a Cohen's k of 0.80.

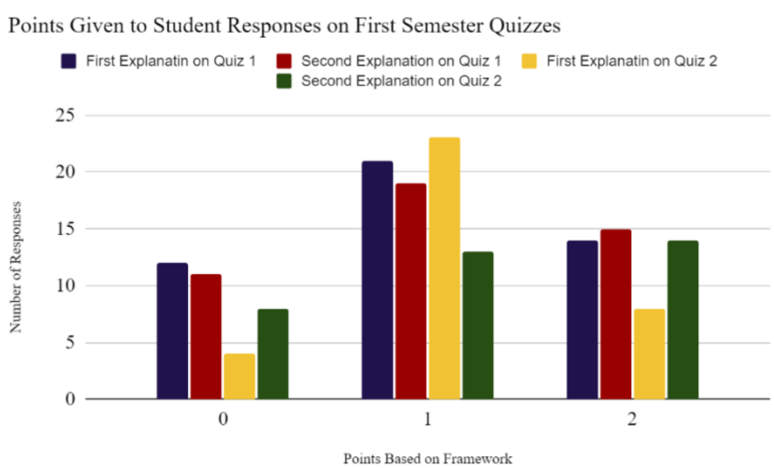


Figure 2: Students (n=47, 45, 35, 35) explanations from the questions on the first semester, Organic I, quizzes scored using the Sandoval Framework (Table 2). The questions asked students to explain their ranking of carbon, explain their ordering of molecules' electrostatic maps, explain their ordering of molecules' electrophilicity (Sample Question 1), and explain which molecule would be expected to have the lowest LUMO answer, respectively.

Together, these question sets in the first semester of Organic Chemistry provided a basis for students' foundational understanding of electrophilicity and related reactivity prior to their learning about esterification reactions and substituent effects. The students were given these questions again at the start of Organic Chemistry II to track their progression. On the first question, again more students (n=70), 33%, ranked the carbon from least to greatest electron density versus greatest to least (30%) as the question asked. More students' explanations were lower scoring, as 41% were level 0 answers, 30% were level 1 answers and 29% were level 2 answers. On the second question, no students correctly matched all of the molecules based on the direction of most to least electron density, yet in their explanations, 29% were level 2, 37% were level 1 and 30% were level 0 responses. For questions originally from the second assemessment, 49% of students (n=68) correctly ranked the electrophilicity of the carbon centers from most to least with 32% of students having level 0 answers, 46% having level 1 answers and 22% having level 2 answers. 92% of students agreed the LUMO value tells you information about the electrophilicity of the molecule, and 67% of students correctly selected the molecule expected to have the lowest LUMO energy. In their explanations 33% were level 0 answers, 46% were level 1 answers and 21% were level 2 answers. The interrater reliability was 92% and 94%, with Cohen's k values of 0.82 and 0.87.

In the third question set (Appendix 3), 77% of students (n=65) correctly selected that benzaldehyde would more readily react with a nucleophile, yet 40% of students had level 0 explanations, 39% level 1 explanations and 20% level 2 explanations. On the second question, 69% of students correctly identified that adding a bromine would increase the reactivity of the ketone/aldehyde, and 34% of students had level 0 explanations, 38% had level 1 explanations and 28% had level 2 explanations. The interrater reliability was 96% with a Cohen's k of 0.92.

Following student's completion of the Spartan activity (Appendix 8), all students (n=20) understood the purpose of the electrostatic potential, ionization and LUMO maps, including the coloring. 80% of students further understood the ionization map is least applicable to evaluating electrophilicity and when explaining how these maps could help you understand the reactivity of the carbonyl in terms of the electrophilicy of the carbonyl carbon of carboxylic derivates, 35% of students had level 2 explanations, 60% level 1 and only 5% level 0. 67% of students correctly predicted the reactions they would be performing in lab in terms of reactivity and 95% of students correctly selected that 4-nitrobenzoic acid would be more reactive. 22% of students had level 2 responses, 33% had level 1 responses and 44% had level 0 responses to answering how the electrophilicity of the carbonyl on the substituted carboxylic acids differed from each molecule and the data that supports this. The interrater reliability was 95% with a Cohen's k of 0.89.

The students then completed the inquiry-based lab (Appendix 7) and wrote a post lab report, which were analyzed for interrelated concepts to determine how well students related their data to the phenomenon (the reactivity of the benzene derivatives to their electrophilicy and LUMO values). Of the student groups who wrote the lab report following the Spartan activity (n=15 student groups), 5 were level 2 responses, 5 were level 1 responses and 5 were level 0 responses. In terms of their cohesivity, 5 scored 0, 3 scored 0.5, 1 scored 0.75 and 6 scored 1. Of the student groups who wrote the lab report before the implementation of the Spartan activity (n=13 student groups), 3 were level 2 responses, 1 were level 1 responses and 9 were level 0 responses. In terms of their cohesivity, 2 scored 0, 3 scored 0.25, 3 scored 0.5, and 5 scored 1.

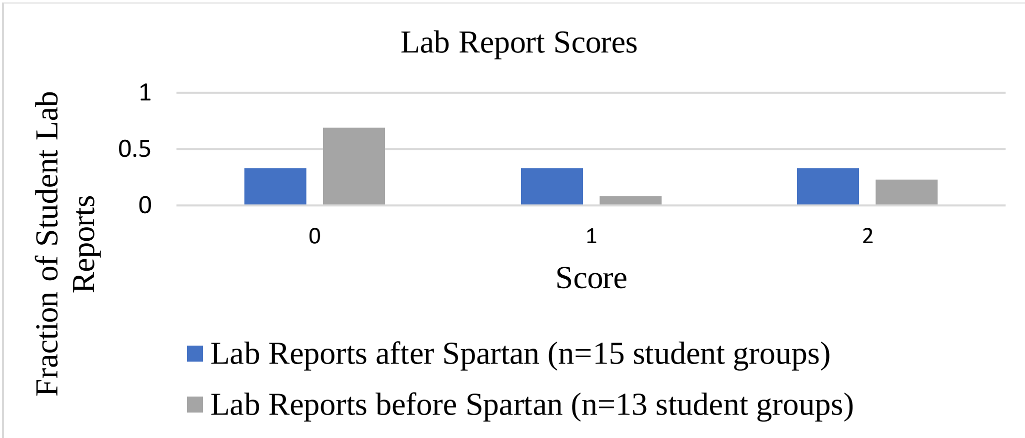


Figure 2: Students (n=15, 13) lab report scores following the completion of the inquiry-based lab (Appendix 7). The reports, written with their small lab groups, were scored using the Sandoval Framework (Table 2) and those scores of students who completed the Spartan assignment (blue) were compared to those who did not (gray).

Conclusion

For the comparison of the first two assessments in Organic Chemistry I, which provided a basis of the students' foundational knowledge from general chemistry to the same assessment questions given at the start of the second semester, unexpectedly, students' scores on decreased (Figure 2). The students came from different sections of Organic Chemistry I, in which they had different professors, who may not have focused as heavily on chemical features. This highlights the possible difference between instructors' instruction. This difference is best highlighted in the students' ability to recognize the features of an electrostatic map versus their explanations in that they could not correctly rank or match the electrostatic potential maps to the molecule but were able to explain the phenomena. This decrease may further be contributed to the fact that these students did not initially fully understand the content nor internalize it in the first semester, but rather memorized it with no metacognition. This supports that learning and long-term memory relies on internalization and metacognition.[14]

Further, students were able to select the correct answer or identify it in a multiple choice or ranking question, yet were not able to fully explain or support their reasoning in their corresponding explanations. This shows the importance of open-ended questions in assessing what students actually understand and the information they are able to convey. This should be investigated further so instructors are able to best assess the concepts they have truly learned and are able to understand and apply, especially relevant for classes with inquiry-based labs. Probing student discussions and monitoring their thinking processes during interviews may further be informative in understanding the concepts students struggle to convey and aid in developing their argument following their selection of the correct answer.

The expectation was that through the assignments, students' ability to use computational methods to explain reactivity of the esterification reaction would increase. This culminated with the comparison of the reports prior to the use of computational methods and those after. Following the implementation of the Spartan activity, more student groups had a level 1 or 2 response in their lab reports (Figure 2). In the reports from before to after the implementation of Spartan, the Cohesivity scores did not change. This aligned with expectations, as while students following the Spartan activity had a better understanding to include the information in their report, which was expected to alter the content of their reports and increase the level of their explanation, yet it was not expected to impact on their writing skills. The average Cohesivity score for students prior to the activity was 0.56, while after it was 0.52. Therefore, the Spartan activity increased student's ability to include relevant phenomena in their explanations of their results in their lab reports as reflected in their scores. This is likely due to the fact that students previously were lacking the ability to synthesize information but when given more elements of information, they were able to better understand and incorporate them into their argument. This leads to the future question, which other phenomena or inquiry-based labs could this model, or another, be effective, especially for students who initially scored low (level 0 responses). This may help students better understand chemistry and enjoy it more.

Limitations:

Possible limitations in this study were a result of the implications of COVID. In the first semester of Organic Chemistry, students' labs were virtual, instead of in person, leaving them to learn all relevant techniques in the second semester. Therefore, there may have been a learning curve in the second semester lab portion of the class. Further, the lecture component of the class was taught virtually, in which, according to the instructors' perceptions, students seemingly struggled with motivation.

Due to time limitations, students' responses were not followed up on, especially in addressing their misconceptions. This also included addressing students' avoidance, in which students, who tended to refer to the textbook, would not solve a problem if they did not see the answer. With increased time, and in other circumstances in the future, these limitations could be addressed.

There are also limitations from the Computational model, Spartan, selected. The model, while comprehensive, does not explain everything. Although explained to students, the model is a tool and not the only way to rationalize the data. Further, different calculation methods and different computer processing abilities using this program will give slightly different numbers.

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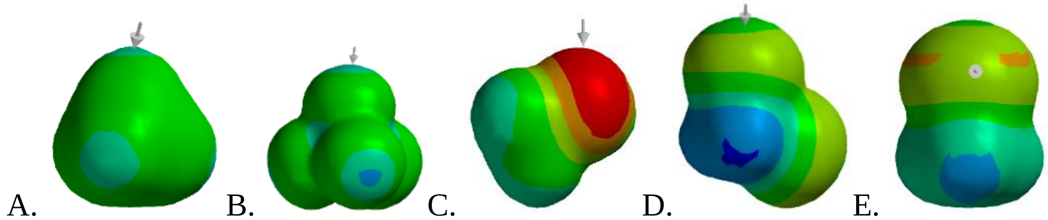
Appendix:

1. Quiz One: The first set of questions given to students on an in-class quiz in the first month of Organic Chemistry I.

a. Rank the carbon on the molecules with the greatest to least electron density on the carbon. It may help to draw the molecules. Explain your answer.

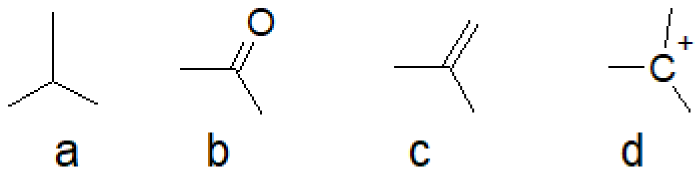
$CHCl_3$, CH_4, CH_3OH

b. Match the electrostatic maps of these molecules ($CHCl_3$, CH_4, CH_3OH) based on the direction of most to least electron density.



2. Quiz Two: The second set of questions given to students on an in-class quiz in Organic Chemistry I after they had reviewed electrophilicity and nucleophilicity.

a. Rank the electrophilicity of the center carbons from MOST to LEAST electrophilic of the below molecules and explain your answer. You may need to consider resonance structures.

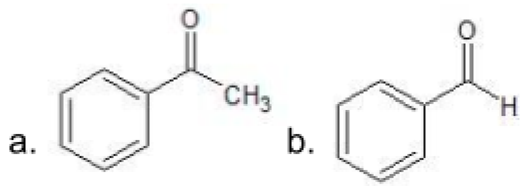


b. True or false: The LUMO value tells you some information about the electrophilicity of a molecule.

c. Which of the molecules would you expect to have the lowest LUMO energy? Explain your answer.

3. Quiz Three: The third set of questions was given to students on an in-class quiz in Organic Chemistry II after they had reviewed esterification reactions and substituents' effects on their reactivity.

a. Which molecule would more readily react with a nucleophile?



b. How would adding a bromine (Br) group 4th position (para) on the ring from the carbonyl, affect the reaction? Explain your answer using your knowledge of the electrophilic properties and substituents effects in esterification reactions previously discussed in this course. Note: these molecules will not undergo esterification, but the first step of the mechanism (acetyl nucleophilic addition step) is the same.

4. Learning Objectives: The learning objectives were given to students prior to the pre-lab Spartan activity and the inquiry-based lab to clearly define the students' learning outcomes.

Following the completion of this lab, students should be able to

- Utilize the IUPAC nomenclature rules to name reactant and product molecules with the use of drawing software, Scifinder, publications or Spartan.
- Understand and correlate the electron effects and interactions to the reactivity and behavior of the molecules.
- Determine the effect and efficiency of different reagents and their product formation and relate it back to the molecules' behavior
- Draw and explain the reaction of the molecules and the reaction mechanism

- Analyze and communicate data, including any reasoning behind the results, supported by literature and connected to the molecules overall properties including analysis of compounds and effect on the reactivity and reaction's outcome.

Syllabus & Overall Student Outcomes (non-lab specific):

- Be able to determine theoretical atom economy
- Work and collaborate in groups utilizing safe laboratory skills and following all safety rules and guidelines.
- Utilize lab techniques from Organic I and II
- Complete pre-lab safety/SDS information
- Utilize green chemistry principles
- Effectively communicate with groups and peers in lab and in written laboratory report
- Be familiar with current relevant literature and include it in a lab report
- Interpret respective data utilizing relevant techniques and determine the obtain product(s)

5. Spartan Activity: The Spartan activity was assigned to students with the learning outcomes and pre-lab questions. It provided step by step directions to students in how to use the software for the applications required for the pre-lab questions, including finding the LUMO values and required maps.

In the previous two classwork, you use Spartan to justify a) acidic of benzoic acid derivatives through the stability of their conjugate bases, electrophilicity of various benzoic acid derivatives, and protonation of acetone as a way to increase reactivity

In CHE 2252 and CHE 2254, you will conduct an esterification of various carboxylic acid derivatives and using Spartan data justify your expected reactivity and compare it to the actual data. Note that electrophilicity was it pertains to the computational data is very helpful, but other factors such as experimenter error, solvents, etc. will not be accounted for. Things such as steric have to be implied based on the minimized energy structure visually, but numerical or maps may not tell you this.

This lab will focus on the effect of the substituents on the benzene's ring reactivity in an esterification reaction. To determine the difference in the reaction's based on starting material and product ratios, the reaction mechanism must be understood. Utilize the Spartan software to computationally determine the molecule's properties, which impacts its behavior and resonance.

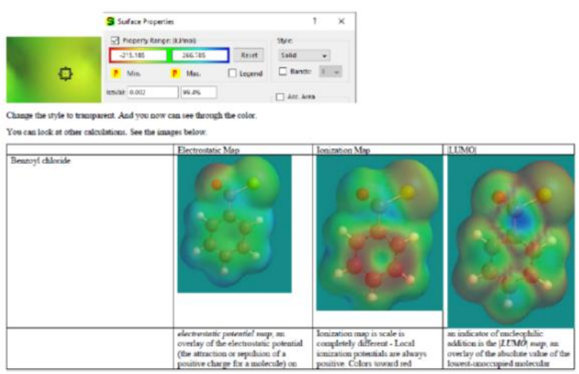
Spartan Esterification Files of Compounds from Dr. Bromfield Lee: https://flsouthern-my.sharepoint.com/personal/dbromfieldlee_flsouthern

As you know, Spartan allows you to build any molecule or open a previously built/saved molecule and perform calculations, view maps and spectra. The above link contains all of the molecular structures required for this Spartan activity. Download the required molecules and open the files through Spartan, or, if you wish to draw the molecule, draw it in the Spartan software and save the file. The link to the Spartan manual is below for additional reference: http://downloads.wavefun.com/Spartan10Manual.pdf

After opening/drawing the molecule, obtain the LUMO energy value, electrostatic map, LUMO map and the ionization map, noting which each means, how they differ between the molecules and their effect on the reaction and copy them into the below table. The link below provides an additional reference for electrostatic maps: https://chem.libretexts.org

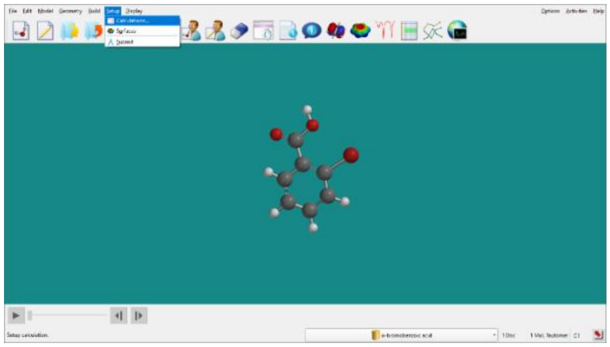
There are different visualizations you can observe in Spartan in addition to the computational values. **<u>Electrostatic potential map</u>**s as you learned in organic I, are an overlay of electrostatic potentials (attraction or repulsion of a positive charge for a molecule) on the electron density. It is valuable for describing the overall molecular charge distribution as well as anticipating the site of electrophilic addition. **<u>Ionization maps</u>** are scales that are completely opposite to electrostatic potential maps. These tell you about the local ionization potential which are always positive. Colors towards red corresponds to a small ionization potential (ionization potential - ease of removing electrons) and colors towards blue correspond to large ionization potentials. Lastly, the **<u>LUMO map</u>** is an indicator of nucleophilic addition, and shows an overlay of the absolute value of the lowest-unoccupied molecular orbital (LUMO) on the electron density. This map by convention shows the color blue to mean the maximum LUMO value and the color red to mean the minimum value.

For today's assignment, we will focus on the LUMO energy and the definition for the visualizations (as well as pasting them in). Next assignment, you will make some correlations. Note that this assignment is what is in your ELN for lab, so doing a good job here is helpful as your complete your ELN.

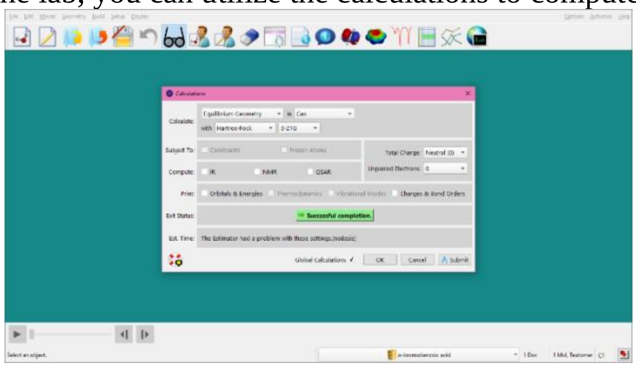


Spartan Tutorial: The images correspond to the text written above them.

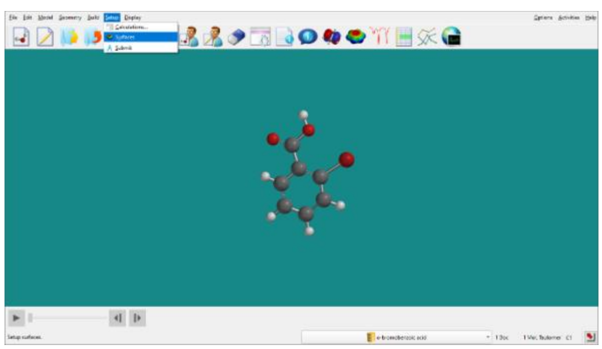
1. Open or draw your desired molecule. Then, under Setup, click on calculations to make sure you have the correct settings.



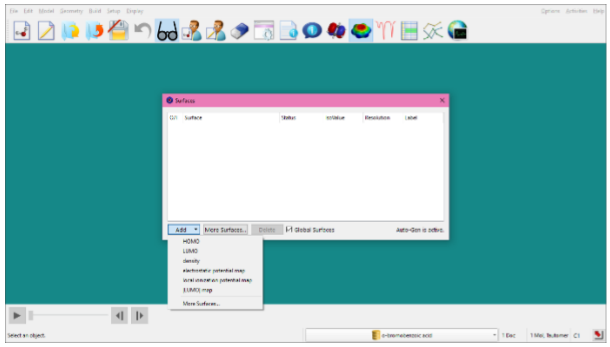
2. Make sure the calculations are Equilibrium Geometry in Gas with Hartree-Fock 3-2-1 G and Neutral Charge. Then click submit until it says successful completion (in the green box). Also note for future use in the lab, you can utilize the calculations to compute IR and NMR spectra.



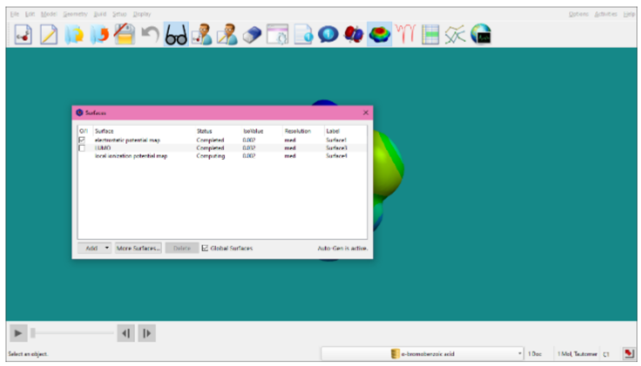
3. Next build your maps. Under set up, click on surfaces.



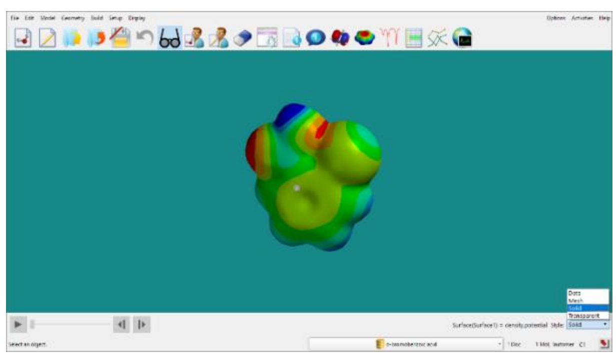
4. Under the Add tab, there will be options for all of the maps you will need to create. To add them, simply click on them.



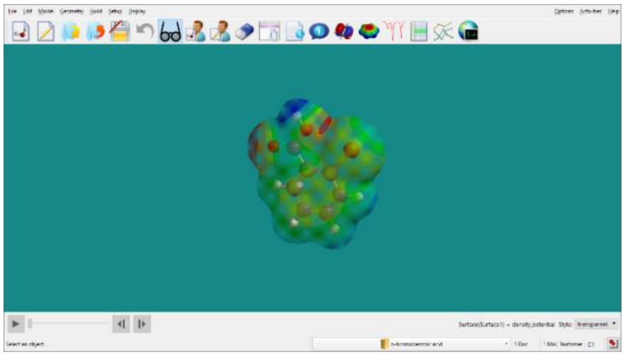
5. Only the selected surface will show up on your molecule. Therefore, make sure that only the surface you want is selected.



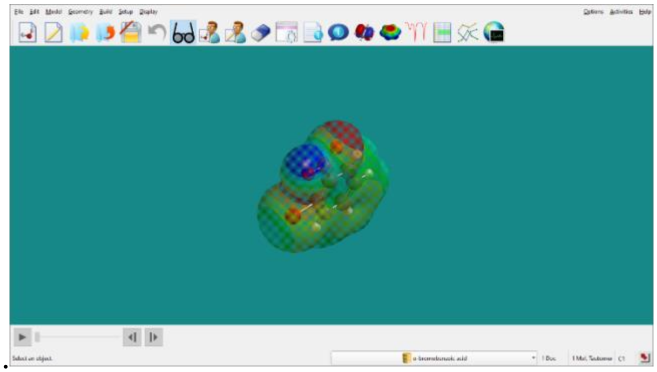
6. The selected surface will appear over your molecule. To change the style, click on the bottom left-hand corner, which will provide you with other options.



7. The transparent style allows you to see the molecule and corresponding surface at the same time, which may be beneficial during your comparison.



8. To move the molecule, click on it and drag your mouse. It can now be copy and pasted into your table and a new surface for another map can be selected



6. Pre-lab Questions: The pre-lab questions were assigned to students before the inquiry-based lab once they had completed the Spartan activity. They focused on the required information, including the LUMO energies, LUMO, ionization and electrostatic potential maps required to encourage students to make predictions about the reactivity of the molecules in the inquiry-based lab and to observe the trends.

Complete the table below and answer the pre-lab questions.

Molecule	**LUMO Energy**	**LUMO Map**	**Ionization Map**	**Electrostatic Map**
Benzoic Acid				
2 - bromobenzoic acid				
4-bromobenzoic acid				
2,5 - dihydroxybenzoic acid				
3,5 - dihydroxybenzoic acid				

4 - bromo 3,5 - dihydroxybenzoic acid chloride				
3- hydroxy benzoyl chloride				
4 - Amino benzoyl chloride				
Cinnamic Acid				

Spartan Related:

1. a. What does an electrostatic map show? An Ionization Map? A LUMO Map?
   b. In your own words, what can each tell you about the properties of the molecule?
2. What do the different colors mean?
3. a. How does the electrophilicity (using the LUMO energy values) of the carbonyl differ from each molecule (generally) and what data supports this?
   b. Are there any trends in the molecules? State the trends observed.
4. Based on your Spartan results, what can you predict about the reactions you will be performing in the lab in terms of reactivity, yield and use of catalyst? Which should be most reactive? Which should be least? Why?

It may help you, prior to completing the lab, to draw the reactants and obtain similar data as in this activity.

Lab Related:

1. Draw mechanism the esterification reaction of the molecule your group is assigned.
2. What factors influence the esterification reactions?
3. What factors in this lab will you explore and what impact do you believe they have on the reaction?
4. What evidence implies success in the reaction?

7. Inquiry Based Lab: The Esterification Reaction Inquiry Based Lab, Unit 2 was provided to students, both in person as traditionally, and virtually due to COVID adaptations.

Techniques and Concepts to Learn or Review:
Continued Green Chemistry methods - Use of microscale laboratory glassware (review the references), solvent choice
Making precise measurements
Extraction
Relationship between intermolecular forces and chemical properties
Spectroscopy
TLC

Objective: At the end of this lab, students will a) collaborate with on the esterification of various benzoic acids to determine trends based on yields, b) examine different reaction conditions and c) compare to Spartan Data.

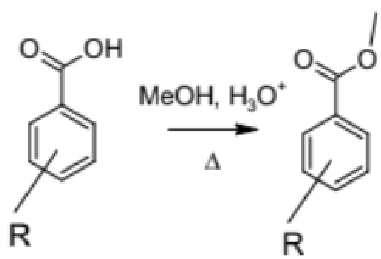
Complete the reagent table which includes, major hazards (these are given in this unit as a guide, but students will be expected to review Safety Data Sheets (SDS) in the future. Hazards associated with incorrect behavior like 'toxic if ingested' are unnecessary, you do not have prolonged exposure, and your room is considered well ventilated. Any compound, including water, may be hazardous and toxic with in appropriate behaviors.

SDS data is provided for you in the box.com folder. SDS contain information about the physical properties of a compound as well as its safety and environmental concerns.

Chemical	**Properties**	**Amount**	**Major Hazard & Specific Precautions**
Sulfuric acid		mL	Highly corrosive, remove gloves and wash hand if it comes in contact with your gloves. Avoid skin contract, wear gloves and goggles at all times.
Amberlyst-15 beads			
Ethyl acetate		For TLC	Skin irritant, wear gloves
Hexanes		For TLC	Skin irritant, wear gloves
Methanol	MW = g/mol Density = g/mL Bpt =	mL	Flammable, keep away from heat and flames
Phosphoric acid			Highly corrosive, remove gloves and wash hand if it comes in contact with your gloves. Avoid skin contract, wear gloves and goggles at all times.
Add your benzoic acid/cinnamic acid	MW = g/mol Mpt =		
Acetone			Flammable, keep away from heat and flames

Introduction:
Esterification reactions produce various molecules that rank from flavorings, protected alcohols or carboxylic acids for further reactions or pharmaceuticals. This is an inquiry-based lab as the outcome of each type of carboxylic acids (mostly benzoic acid) is not known. So why are you doing this, you will discuss as a class the trends you observed in the data to determine how substituents on the ring may influence the reaction. The aim of the first reaction is for you to use new green methods such as Amberlyst-15 as well as come up with a rationale for the trends. This experiment has three reactions you will compare, but also you will have data from your entire class. This is one way that we can eliminate waste, by having data collected by your classmates rather than your group completing over 30 reactions yourselves. This experiment compares catalyst choice and examines the trend of the substituents on your molecules.

Scheme 2.1: Esterification Reactions



<u>*Carboxylic Acid Assignments will be in your notebook and will be one of the following:*</u>

3,5-dihydroxybenzoic acid
2,4-Dihydroxybenzoic acid
2,5-Dihydroxybenzoic acid
2-Bromobenzoic acid
3,5-dihydroxybenzoic acid
4-Aminobenzoic acid
4-bromo-3,5-dihydroxybenzoic acid
4-hydroxybenzoic acid
Benzoic acid
trans-cinnamic acid

Prior to lab, you will make a prediction about how the substrates influence the rate and yield of the reaction and use the Spartan Assignment to help you.

You will use the assigned carboxylic acid, methanol and acid catalyst to perform the following reactions. You will complete reaction 1 in the first week, reaction 2 in second and reaction 3 in the third.

Reaction 1:

You will use sulfuric or phosphoric acid (one will be assigned) as your acid catalyst.

Reaction 2:
You will use Amberlyst-15 beads as your acid catalyst.

Reaction 3:
Reuse the Amberlyst-15 beads to compare the re-usability.

Method

To a solution of the assigned benzoic acid (0.5 mmol, same as 0.0005 mol) in methanol (1 mL), and your assigned acid catalyst was into a 5 mL conical vial. The reaction mixture was refluxed for **1 hour** (in a water bath (reflux means that your reaction mixture MUST boil even if the water bath is not boiling). Start timing when the mixture starts boiling only (Figure 2.1). *Why may MeOH boil even if the water bath is not boiling?*
Figure 2.1: Reference:
https://www.thevespiary.org/rhodium/Rhodium/chemistry/2cb/Lycaeum%20)%20Leda%20)%20Diagram%20o f%20reaction%20vessel%20with%20reflux%20condenser.htm, Last accessed 1/6/2019.

When sulfuric acid was your catalyst: Use two drops of the acid. Neutralize with sodium bicarbonate or sodium carbonate (10%) once the reaction is completed and cooled. Extract with 1 mL ethyl acetate twice. Remove the aqueous layer and keep the organic layer. Keep the aqueous layer until you are done with the experiment to ensure you have the correct layer. Dry the organic layer and place it in a pre-weighed dry vial (10-15 mL should be fine – look in the vial drawer). The reaction was then checked for reaction completion using TLC.

When Amberylst beads were used as your catalyst: Use a spatula tip of beads (they are hard to weigh). Remove them after the reflux is completed and cooled. Rinse them with ethyl acetate over your reaction vial (carefully not to lose them) and place in the container for used Amberlyst for the specific carboxylic acid (you will reuse them). Place in a 10-15 mL vial from the vial drawer that was clean, dried and pre-weighed. Flush out your conical vial with 2 mL of ethyl acetate. Obtain a TLC.

The solvent was then removed by evaporation in a water bath. The product is often a white solid. Obtain an IR, weight (when the vial is cool and dry), and GC-MS. In week 1 you will use one benzoic acid and the second week use the other. Obtain your GC-MS data and analyze it by the next week and post the summary information to your class immediately. Your instructor will deduct points if you do not post your data to your peers by the week following each reaction in the lab.

While you wait on your reactions in the lab, get an IR and GC-MS of the starting carboxylic acids for comparison.

Do not store samples in conical vials, only in storage vial from the vial drawer.

Clean up:

Wash all your reaction vials after removing excess material. Rinse with Alconox and water. If the material is hard to remove, rinse over the waste bottle with acetone.
Rinse again with soap and Alconox.

Discard your samples in the waste container after you have reviewed your GC-MS and IR data. You should keep your samples until you are sure you do not need to re-run them.

Clean your counters, sink area, hood (including the counter in the hood), replace all chemicals, close the waste bottle and replace all solvents before leaving. Your professor will deduct points from your performance grade if there is any mess left in the lab. If there are any messes left around any instrument, points will be deducted from everyone's grade.

Data Analysis:
Consider all the green aspects about the lab.
Analyze all the classes data (all sections). What can you deduce from the carboxylic acid structures and the amount of product formed? It is expected that they may not all go to completion (may be some many not react at all). How does this data compare to your prediction? What information can the resonances and molecular modelling data suggest that can explain the trend. Calculate the atom economy.

Since multiple groups are running the reactions, it will help provide enough information to avoid outliers. Provide an analysis of the yield and spectra for each week to determine the success of the product.

If your lab report does not analyze the data for the entire class, you will be deducted a large portion of your points.

Your Spartan analysis will be posted in your notebook and is to be completed on your own and analysis reported in your report. Your instructor will not help you with your Spartan assignment. Review methods from Organic I.

Your report grade will include the success of your report, so work quickly but carefully.

8. Post-lab Assessment Questions:

Table specific: Explain the results you see with respect the electrophilicity of the carbonyl carbon. Hint: which piece of data is most relevant and discuss the trends. This will be a paragraph or two.

Answer:

Come up with another benzoic acid molecule not in this activity that you believe would be more electrophilic. Explain.

Answer:

1. What does an electrostatic map show? An Ionization Map? A LUMO Map? What can each tell you about the properties of the molecule?

Answer:

2. What do the different colors mean? (for each)

Answer:

3. What was the trend in reactivity in the LUMO values? Do you see any relationship to the maps?

Answer: