Type and Frequency of Errors Student Make While Solving Organic Chemistry Mechanisms

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Abstract

This report is an exploratory study of students learning from their own mistakes through an instructional technique using carbonless copy paper (CCP). The main purpose of this report is to present and discuss the findings of the most common conceptual errors that students make in second-year organic chemistry questions. Some of the more frequently appearing errors were due to misconceptions in the role of acid catalysis, formal charges on intermediates, and determining the correct mechanisms under specific conditions. A secondary purpose of this study is to present a preliminary analysis of patterns of student's progress across multiple organic chemistry problems. Findings from this research study will serve to provide data on students' problem solving skills to inform future educational studies, curriculum designers, and instructional activity developers. Data from this study will also be utilized to formulate potential organic chemistry questions for an online prototype activity in hopes of helping students learn organic chemistry more effectively.

Introduction

Learning from errors is a popular domain studied today in the field of education. Studies have suggested that students can gain a better conceptual understanding when they learn from their own mistakes. Learning organic chemistry involves solving problems that can sometimes be particularly challenging for students as mechanistic-type problems are open-ended and often involve a series of decision-making steps within only one problem. As a result, a carbonless copy paper (CCP) activity was devised to help support students' learning processes as well as for research purposes in gaining a wider perspective on learning from error correction. The technique involves students to first attempt the chemistry problem on the first sheet of CCP. During a thorough explanation by the instructor of the correct methodology to answering the problem, students were asked to correct their own mistakes on the second sheet of CCP. Data from these two sheets of CCP were obtained to be used for further research and developmental questions for future instructional activities.

There are several theories that can be applied to this study about how students are able to gain conceptual understanding of material through learning from their own errors. Ohlsson's (1996) view on the theory of learning from errors is that individuals obtain skills by perceiving and correcting their own mistakes; however, this requires the learner to have adequate knowledge of the task at hand. In the CCP study, students were taught by an instructor prior to answering and correcting their own errors in the CCP activity. During the act of learning from errors, Ohlsson states that there are two main cognitive functions that are being utilized: error detection and error correction. Error detection involves learners to be able to recognize their own mistakes and be able to make comparisons of their own work with the correct solutions (Ohlsson, 1996). The second cognitive function, error correction, entails the learner to fix the error made,

thereby correcting misconceptions in the fundamental knowledge and familiarizing one-self to techniques of solving a problem (Ohlsson, 1996). In this study, Ohlsson's error learning theory may be directly applied to students learning organic chemistry as it anticipates that they are able to detect their own mistakes with sufficient knowledge of the chemistry problem, while subsequently making corrections to their own work, if necessary.

In this exploratory study, the primary purpose is to present and discuss the most common conceptual errors in second-year organic chemistry questions. A secondary purpose is to present a preliminary analysis of patterns of student's progress across multiple organic chemistry problems. The findings from the CCP activities will serve as basis for future research studies, and will be used to formulate potential chemistry questions for an online prototype activity in hopes of helping students learn organic chemistry more effectively. Moreover, a method of organizing data sets using PivotTables will be discussed.

Method

Participants

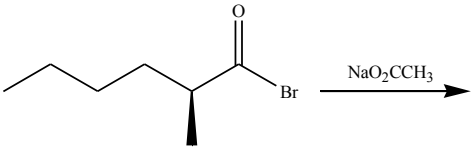
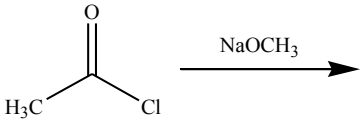
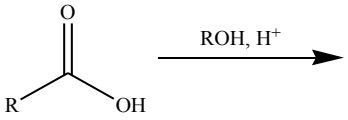
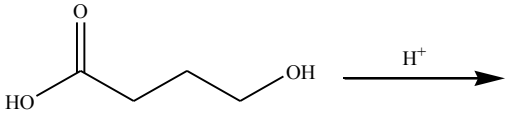
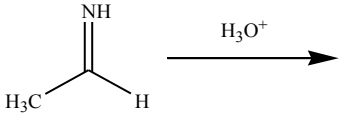
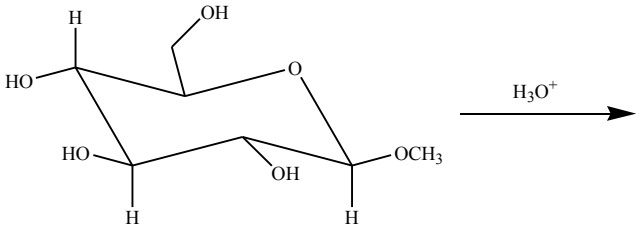
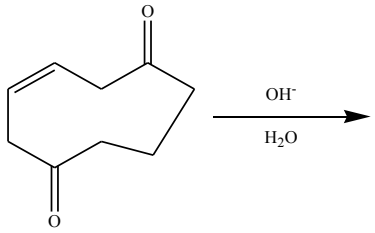
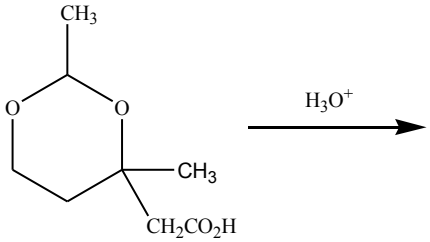
The study participants included 524 second-year UBC students during the winter term in 2010. There were 259 and 265 students in sections 122 and 199, respectively, from the second-year organic chemistry course for biological sciences (CHEM 233). The ratio of female to male students was 64:36. The actual number of students completing each CCP assignment varied from approximately 400-530 students due to absences or students choosing not to participate. Most of those present during a particular class activity participated, although some students did not hand in a CCP.

Carbonless Copy Paper Activity Description

The CCP activity is an instructional technique that provides students with the opportunity to attempt a given problem and subsequently correct their own mistakes. A total of eight mechanistic organic chemistry questions were given to students to attempt on various days within the span of approximately two and half months. The instructional method of each problem was the same for all eight questions. The instructor presented a CCP question on the projector screen during class time, ensuring all concepts in the problem had already been covered so that students had enough background knowledge to attempt the question. Students were asked to attempt the question on the first page of the CCP and were allotted ten minutes to complete the problem (trial period). After the allotted time, students were to hand-in the first page of their CCP. The correct answer was then provided through an explanation by the instructor on an interactive tablet PC (explanation/corrections period) with class discussion. During this time, students who encountered mistakes in their first attempt were to correct their own mistakes on the second CCP, which had a copy of their original work from the first CCP. Figure 1 illustrates an example of an original notepad written by the instructor during an in-class explanation of October 19th CCP answers for class section 122. Please refer to Appendix C for more sample PowerPoint slides drawn during in-class explanations. After the explanation/corrections period, the second CCP page was collected and students kept the last CCP page, which included both their attempt at the problem and corrections for future reference. Students were given a small participation mark each time they completed a CCP question as an incentive for their participation. Table 1 displays a list of the organic chemistry mechanism problems given to students during class time in the format of CCP. Many problems involved similar concepts including nucleophilic acyl substitutions and acid catalyzed conditions.

Table 1

List of carbonless copy paper questions for second-year UBC students

Completion Date (2010)	Chemistry Problem: Draw the mechanism of the given reaction.	Reaction Type
1) October 19th		Nucleophilic Acyl Substitution
2) October 21st		Nucleophilic Acyl Substitution
3) October 26th		Nucleophilic Acyl Substitution
4) October 28th		Nucleophilic Acyl Substitution
5) November 9th		Imine Hydrolysis
6) November 23rd		Acetal and Hemiacetal Hydrolysis
7) November 30th		Aldol Condensation
8) December 2nd		Acetal and Hemiacetal Hydrolysis with Nucleophilic Acyl Substitution

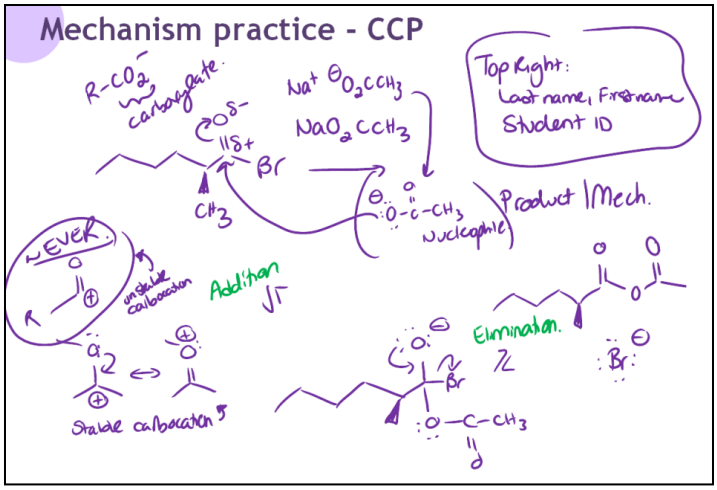


Figure 1. Actual PowerPoint slide drawn during October 19th carbonless copy paper activity

Qualitative Coding

In order to prepare the student responses for analysis, a coding scheme for each CCP question was developed. A coding scheme consists of letters and numbers representing correct and incorrect electron movements, formal charges, intermediates, and products. Following this detailed coding of student work, the most common type of errors students make while solving the various problems was tabulated.

Generation of coding scheme. As an example, the development of the coding scheme for the October 19th mechanism will be described. Firstly, the mechanism process was described by steps involving electron movements, intermediates or product. This nucleophilic acyl substitution reaction involved a total of seven steps. It is important to clarify that, in this study, the definition of a "step" is defined by the research team as an electron movement, and intermediate or product drawn. The actual number of steps required to complete this mechanism in chemistry terms is two (elimination and addition step). Please refer to Appendix A for the entire mechanism. Each of the seven steps can be assigned a diverse set of codes. A list of some of the codes used for October 19th CCP question can be found in Table 2. To show an example of

how coding was done, Student A's work shown in Figure 2 was assigned the codes listed in Table 3. Figure 3 displays a screenshot of how the codes for Student A's work were actually inputted into Excel. Each column marked a different step in the mechanism followed by a column labeled as "Corrections". The correction column was always related to the column step on its left. Students who made errors in the first attempt of the problem were asked to correct their mistakes on the second page of the CCP, which is shown in Figure 4. For each mistake made, students were assigned the correction codes from 0 to 2 in the corresponding corrections column. For meanings behind these codes, please refer to Table 4. A total score and additional codes under the "Comments" column was also given for each student during coding. Details of the amount of points given for each coding column and the meaning behind the "Comments" column can be found in Appendix B. The complete October 19th coding scheme can be found in Appendix B.

Table 2

A list codes used for October 19th carbonless copy paper question (More codes can be found in Appendix B)

Type of step: Dissociation Step

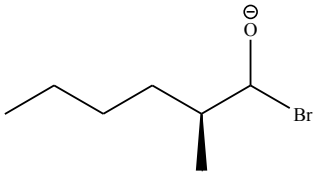
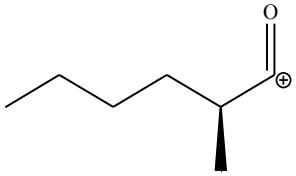
Code	Name	Description
Y	Yes	Student dissociated the salt molecule
N	No	Student did not dissociate the salt molecule

Type of step: Electron Flow Arrows

Code	Name	Description
RS/RE	Right Source/ Right End	Electron flow arrow indicates a right starting and end point
WS/WE	Wrong Source / Wrong End	Electron flow arrow indicates a wrong starting and end point
RS/WE	Right Source / Wrong End	Electron flow arrow indicates a right starting and wrong end point
WS/RE	Wrong Source / Right End	Electron flow arrow indicates a wrong starting and right end point
A	Absent Arrow	Did not draw the arrow in mechanism
B	Backwards Arrow	Opposite electron flow direction

WT(X)	Wrong Time Arrow	Correct arrow occurred during wrong step, X

Type of step: Intermediates

Code	Name	Description
R	Right Intermediate	Intermediate drawn correctly
W1	Wrong Intermediate 1	
W2	Wrong Intermediate 2	
NFC	No Formal Charge	Intermediate drawn with no formal charge (code can be for right or wrong intermediates)
WFC	Wrong Formal Charge	Intermediate drawn with wrong formal charge (code can be for right or wrong intermediates)
A	Absent Intermediate	No intermediate drawn

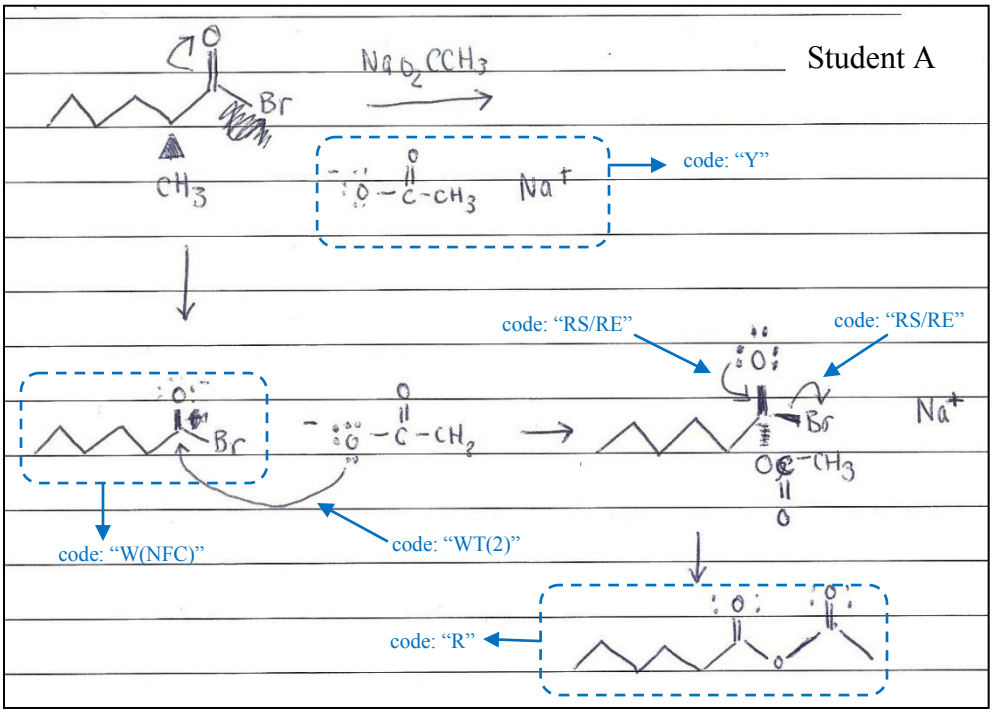


Figure 2. Student A's work for October 19th on the first carbonless copy paper with added codes (blue) as reference

Table 3

Codes assigned to Student A in Figure 2 for October 19th carbonless copy question

Coding Columns	Code
1) Dissociation of Salt	Y
2) Nucleophile Attack Arrow	WT(2)
3) Pi Bond Deformation Arrow	RS/RE
4) Intermediate 1	W(NFC)
5) Leaving Group Arrow	RS/RE
6) Pi Bond Formation Arrow	RS/RE
7) Final Product	R

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Student Name	1) Dissociation of Salt	Corrections	2) Nucleophile Attack Arrow	Corrections	3) Pi Bond Deformation Arrow	Corrections	4) Intermediate 1	Corrections	5) LG Arrow	Corrections	6) Pi Bond Formation Arrow	Corrections	7) Final Product	Corrections	Score	Comments
2	Student A	Y		WT(2)	1	RS/RE		W(NFC)	2	RS/RE		RS/RE		R		3	W.1.2.3.8.
3	Student B	Y		A	1	A	1	W2	1	WT(1)	1	A	1	R		1	C.1.2.3.4.5.8.
4	Student C	Y		RS/RE		A	1	A	1	WT(1)	1	A	1	R		1.5	C.1.2.3.4.6.8.

Figure 3. A screenshot of converted quantitative data in Excel of October 19th carbonless copy question

Table 4

List of definitions for corrections codes

Code	Definition
0	Student did not attempt to correct the mistake
1	Student corrected mistake properly
2	Student attempted to correct mistake but was wrong (incorrect correction)
Blank	Step was already correct, therefore, did not need to make a correction

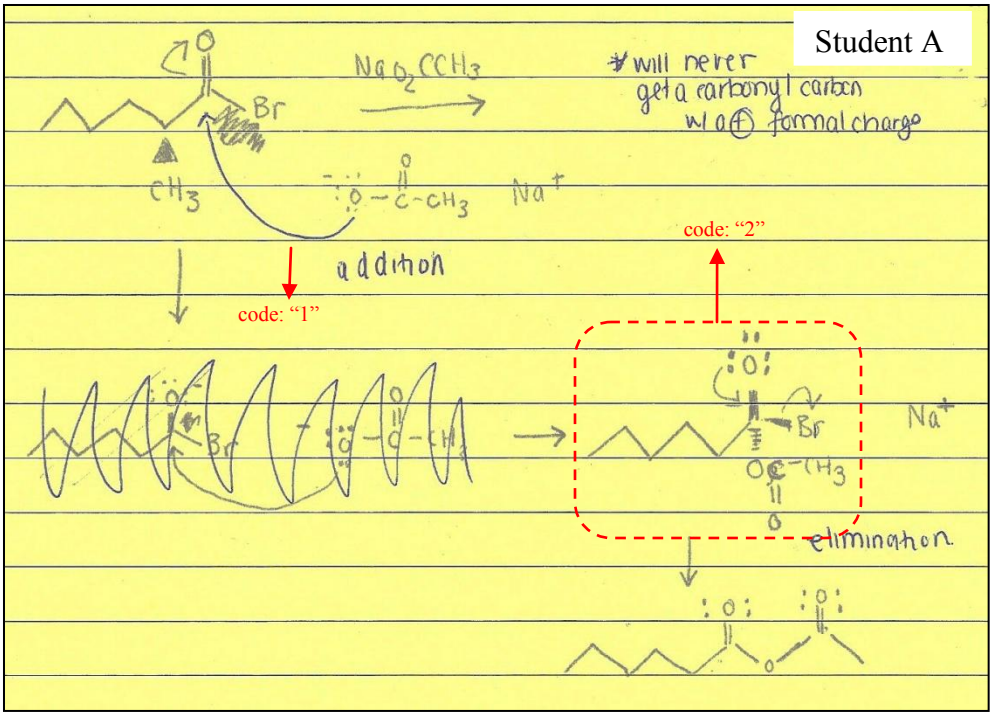


Figure 4. An example of a student A's work on the second carbonless copy paper with added codes (red) as reference

Inter-rater reliability. Since coding qualitative data involved more than one research assistant to interpret the work of students and convert the data into codes, the results of the conversion can sometimes be inconsistent. Therefore, inter-rater reliability (IRR) was used to evaluate and minimize discrepancies in the conversion of data and ensure the generated results are useful for further analysis. IRR involved the research team to code identical sets of twenty random students within one CCP question. Subsequently, the two sets of converted data by different coders are compared and the following equation is used to calculate an IRR score:

$$\left(\frac{Number\ of\ discrepancies - Total\ number\ of\ coded\ answers}{Total\ number\ of\ coded\ answers}\right) * 100$$

where the total number of coded answers is defined as the product of the number of steps in the mechanism and the number of students compared in the IRR analysis. IRR scores of 90% and

above were acceptable, and scores between 80% and 90%, exclusive, were considered to be sufficient; however, possible revisions might have been carried out to improve the IRR. Any scores of 80% and lower required either a thorough revision of the coding scheme, re-training of the research assistants in coding, or re-coding of data.

Data Analysis

In order to be able to efficiently analyze and process the large amounts of data, pivot tables were used. PivotTable is a tool in Excel software that allows for many useful applications in spreadsheets involving a large mass of data. In general, the PivotTable function allows users to organize large lists of data by grouping information, or filtering data for easier analysis. Secondly, it can quickly perform different functions automatically on a data set such as counting, and providing the sum, average, product, maximum, minimum, or standard deviations. For our study purposes, the "count" function was utilized to count number of certain mistakes, answers, and corrections. Lastly, PivotTable is very useful in summarizing data, allowing the user to manipulate data sets to gain several alternative perspectives.

Determining the most common conceptual errors. For the investigation of the common conceptual errors of each CCP activity, pivot tables were formed to analyze the coded data. In the initial analysis, simple counts were applied to determine the most common codes appearing in each mechanistic step. As shown in Figure 5, a sample pivot table was arranged to view the most commonly occurring answers of the first step (nucleophile attack arrow) of October 19th CCP question. Determining the most frequently occurring codes was a strategy used to determine common conceptual errors occurring within the problem.

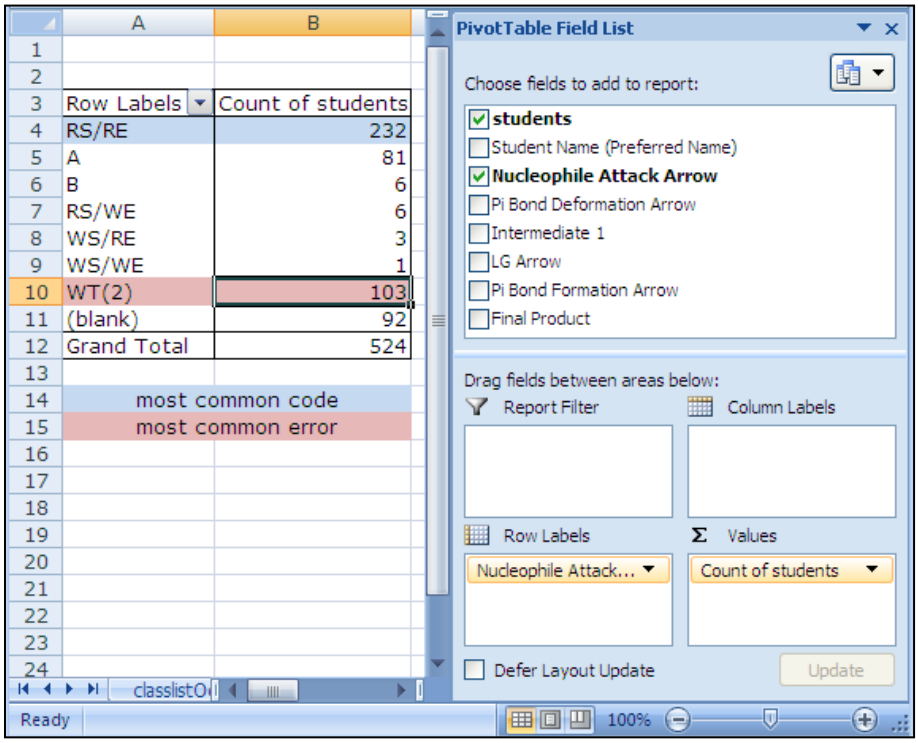


Figure 5. Pivot table view of count of students per code for October 19th carbonless copy paper question

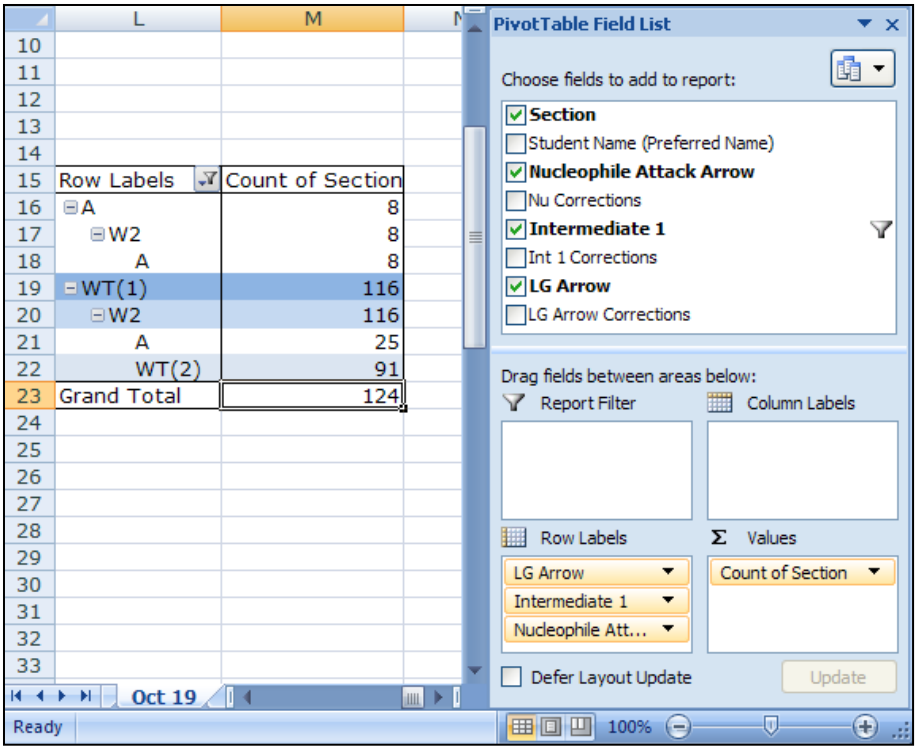


Figure 6. Pivot table view of S_N1 conceptual error for October 19th carbonless copy paper question

Following analysis of commonly occurring codes, further in-depth analysis was carried out using PivotTable manipulations to translate errors into conceptual problems in CCP questions. After determining a type of conceptual error, a combination of codes was grouped together to indicate the specific codes a student must have obtained to be able to suggest that they made the particular conceptual error. For example, Figure 6 shows a pivot table illustrating the number of students obtaining a "S_N1-type" conceptual error in October 19th CCP where the halide leaves first forming an unstable carbocation intermediate. It is then followed by a nucleophilic attack on the carbocation. An illustration of this error is shown in Figure 10 of the results and discussion section. In this case, the combination of codes indicating an "S_N1 type" error includes a "WT (1)" for the leaving group arrow, "W2" for intermediate 1, and "WT (2)" for the nucleophilic attack arrow. By including the combination of the three steps that make up

the "S_N1-type" conceptual error in a pivot table, it is able to quickly count the total of number students making the particular conceptual error. This function is shown in Figure 6, where a total of 91 students made an "S_N1-type" conceptual error. A clearer representation of the pivot table in Figure 6 is shown in Figure 7, which is illustrating the same information but viewed in a tree-form perspective. This is useful for determining the amount of students carrying out a particular combination of codes which make up a conceptual error, as suppose to a single isolated misstep. All CCP questions listed in Table 1 were analyzed except for December 2nd CCP question due to the limited time frame of this exploratory study.

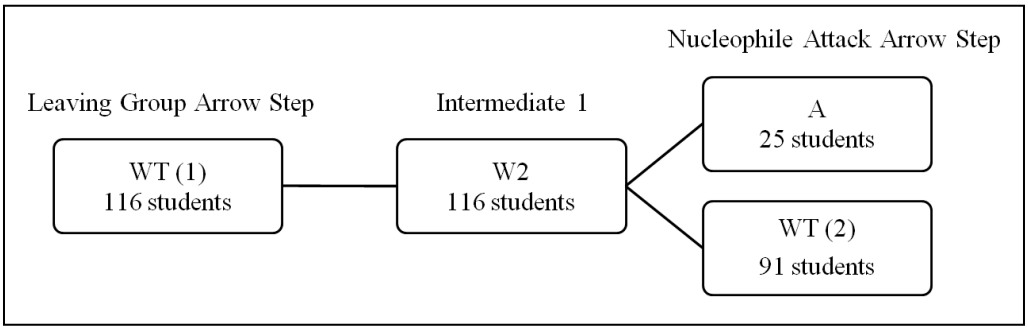


Figure 7. Tree-form perspective of students making a "S_N1" type error in October 19th carbonless copy question

Method of analysis for student progress over multiple chemistry questions. For the investigation of the students' progress across CCP questions, specific mechanistic steps were compared across similar types of questions. To simplify the analysis, the outcome of each step was categorized into two groups: correct versus incorrect. To provide an example, the analysis of student progress with the initial protonation step across four acid-catalysis questions was conducted, shown in Figure 8. Each question was designated a letter and a "w" was added to the codes that indicated the student obtained a wrong answer for the initial protonation step. The altered data was then analyzed in pivot tables, shown in Figure 9. In this case, identical steps

across different CCP questions were used instead of a combination of different steps within one CCP question, which was mentioned previously in the common conceptual analysis section.

	D	E	G	H	J
2		Oct-26	Oct-28	Nov-09	Nov-23
3	Student	Initial Protonation	Initial Protonation	Initial Protonation	Initial Protonation
212	Student C	Aw	Bw	C	D
213	Student D	Aw	Bw	C	D
214	Student E	Aw	Bw	Cw	D

Figure 8. Example of multiple question analysis

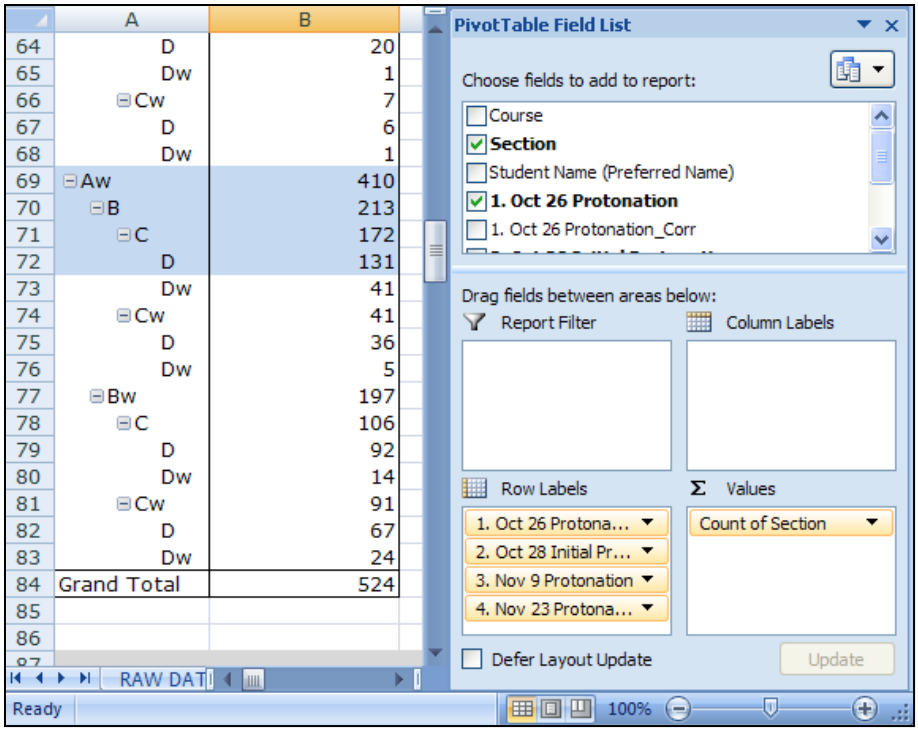
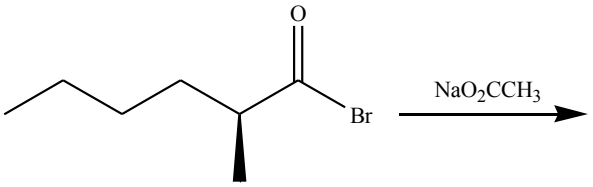


Figure 9. Pivot table view of analysis of student progress

Results & Discussion

Analysis of Common Conceptual Errors of CCP Questions

October 19th



This question assesses students on the concept of acyl nucleophilic addition substitution reaction, using a salt as a nucleophile source without providing the reaction product in the question. It involves the formation of a tetrahedral intermediate, following an expulsion of the weakest base, which is the halide substituent. Of the 524 students, 92 students did not complete this CCP question, which left a total of 432 students in the sample. The percentage of students answering this question completely correct was 23.4%. Of the students who answered the question incorrectly, 26.9% of them expelled the bromo-halide group first which created a highly unstable carbocation in intermediate 1. In addition, 78.4% of students, who expelled the halide group first, further carried out the reaction in an "S_N1-type" conceptual error as illustrated in Figure 10. The remaining 21.6% of students were unable to move past intermediate 1, resulting in answers that were blank past this point.

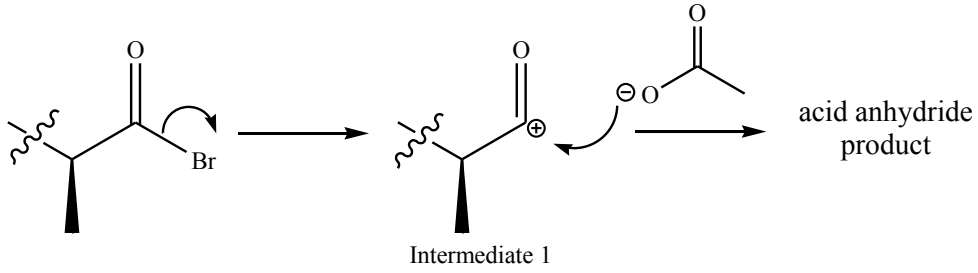
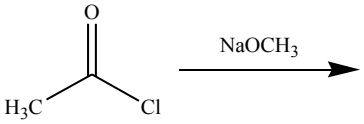


Figure 10. Common "S_N1-type" conceptual error in October 19th carbonless copy paper question

Another common mistake was the lack of initial dissociation of the anionic nucleophile. About 21.7% of students who completed the activity did not recognize that NaO_2CCH_3 was a salt that could easily be dissociated in an aqueous solution. Of these students who didn't show nucleophile dissociation in their initial step, 12.8% illustrated the proceeding intermediate correctly anyway without the sodium ion, and without any indication that the salt had been dissociated previously. This suggests that those particular students may have actually understood the dissociation process but failed to indicate it in their answers. As a result, no marks were deducted for these students as the dissociation step was implied.

October 21st



This question also tested students' understanding of acyl nucleophilic addition substitution reactions, but with an alternative reagent and nucleophile. This question re-examines students' understanding of using a nucleophile to attack the electrophilic carbon of the carbonyl, which results in a tetrahedral intermediate followed by expulsion of the halide group. Of the 524 student sample, 80 students did not complete this CCP question which left a total of 444 students in the sample. More than half the students who completed the activity (57.4%) obtained a completely correct mechanistic answer. There was a large increase in the number students obtaining the correct answer in the second CCP question, which was approximately 2.5 times greater than the first CCP question. This suggests students do better with more practice of a certain type of question even with slight variations in the nucleophile and reactants. Taking a closer look at individual steps of the question, 23.4% of students failed to dissociate the

nucleophile, which is similar to the case in October 19th. However, this time a majority (75.0%) of the students who used the nucleophile to attack in its salt form, also illustrated the proceeding intermediate correctly anyway without the sodium ion, which is six times more students than the previous question. An example of this is shown in Figure 11.

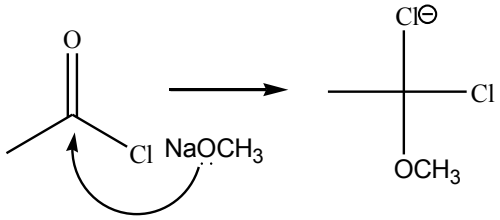
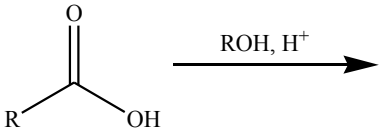


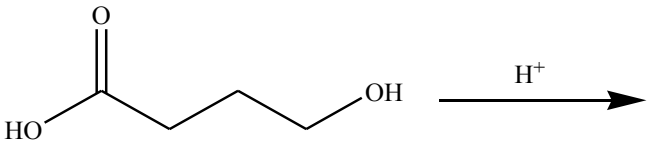
Figure 11. Example of an undissociated sodium methoxide attacking the carbonyl intermediate forming the "correct" intermediate

October 26th



This CCP question examined students' understanding of another acyl nucleophilic substitution-type reaction also involving acid-catalyzed esterification. Students were given a general carboxylic acid as starting material along with a general alcohol and acid catalyst. In this question, 65 students of the total possible 524 student sample did not submit their CCP assignment, which left a total of 459 student assignments for analyzing. A very small percentage of the class (0.02%) answered this question completely correct. The most frequent mistake with this mechanism was failure to use the acid catalyst when carrying out the reaction. More than half the students who completed this activity (56.0%) made this conceptual error. This suggests students either did not grasp the concept of acid-catalyzed reactions or did not recognize the reaction conditions given in the mechanism.

October 28th



This CCP question checked students' understanding of another acyl nucleophilic substitution-type reaction under acid-catalyzed reactions, but this time involving an intra-molecular process. Of the 524 student sample, 136 students did not complete this CCP question, which left a total of 388 students in the sample. A very high percentage of the class (89.4%) answered this question completely correct. The most frequent conceptual error made by students in this question was during the initial protonation step where students had difficulty in choosing the correct protonation site. A total of 18.6% of students protonated the wrong oxygen. Furthermore, 68.0% of those students chose to protonate the hydroxyl group further away from the carbonyl, while the remaining 31.9% chose to protonate the hydroxyl group of the carboxylic acid. The most common erroneous mechanistic path that students took after that point was either one of two routes: they performed a nucleophilic attack which expels either a protonated or non-protonated hydroxyl group as illustrated in Figure 12, or made the protonated hydroxyl group leave without a nucleophilic attack (dehydration) shown in Figure 13. About a third of students chose the nucleophilic attack route, and another third chose the dehydration route. The question of how students obtained the extra proton or positive charge on the carbonyl oxygen in Figure 13 is unclear. Overall, for students who made mistakes in this question, the greatest challenge was determining the correct protonation site.

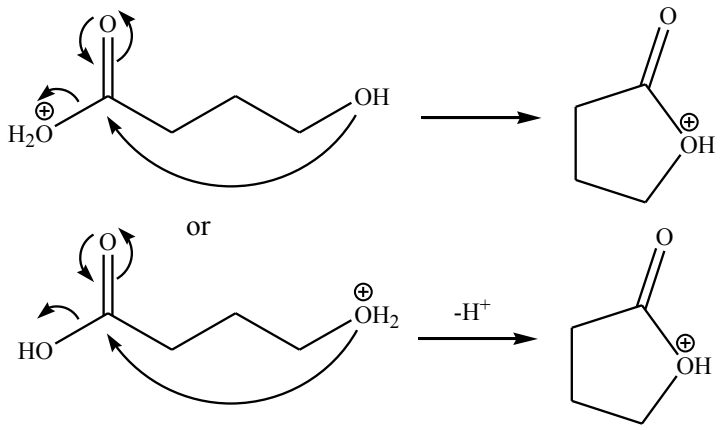


Figure 12. A common conceptual error made in October 28th carbonless copy paper question: nucleophilic attack of incorrectly protonated hydroxyl intermediate

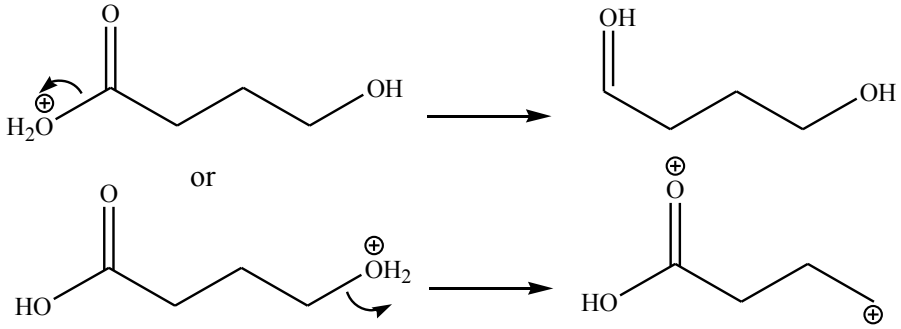
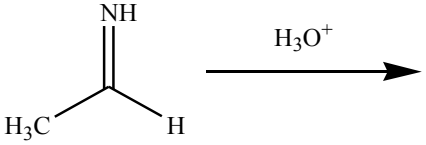


Figure 13. A common conceptual error made in October 28th carbonless copy paper question: dehydration of incorrectly protonated hydroxyl intermediate

November 9th



November 9th CCP question tested students' understanding of another acyl nucleophilic substitution-type reaction under acid-catalyzed reactions, but this time involving an imine as the starting material. Of the 524 student sample, 74 students did not complete this CCP question, which left a total of 450 students in the question sample. The percentage of students answering

this question completely correct was 15.8%. The concept that students had most difficulty with was the correct order of elimination of the amine group after arriving at intermediate 4 (Figure 14A). The correct mechanism involves a simultaneous formation of the carbonyl and elimination of the amine group shown in Figure 14C. Close to 15% of students eliminated the amine group without simultaneous formation of the C-O double bond and about 10% of students simply just deprotonated the hydroxyl group of intermediate 3 before the elimination step as demonstrated in Figure 14A and Figure 14B, respectively. The percentages include similar intermediate derivatives from students who did not protonate in their initial step of the mechanism.

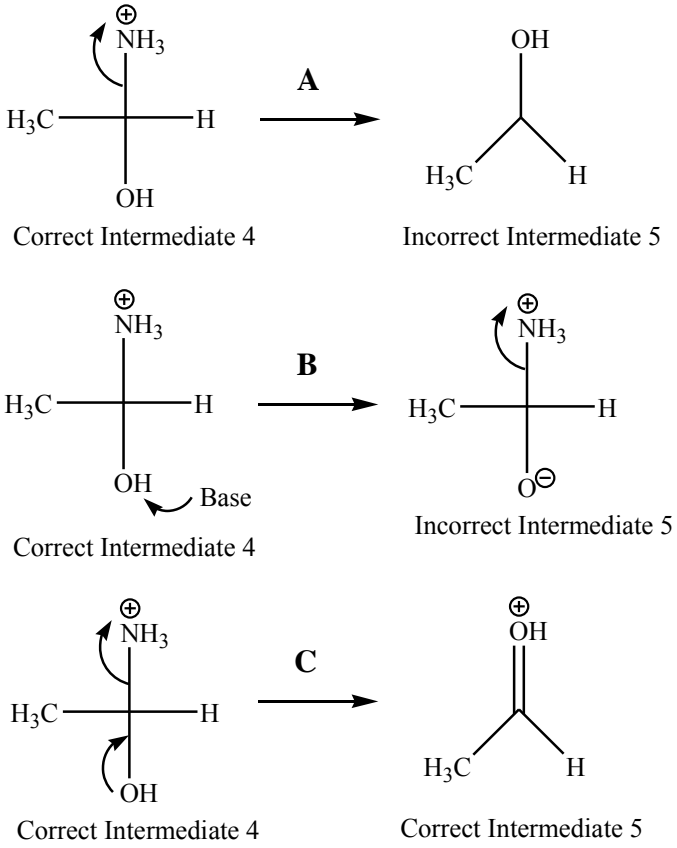
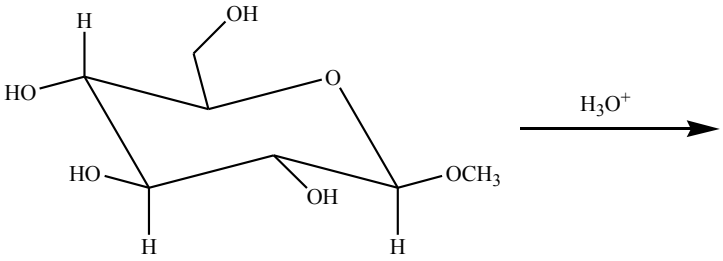


Figure 14. Examples of students' work in November 9th carbonless copy question: (A, B) Incorrect and missing electron movement from intermediate 4 to 5 (C) Correct electron movement from intermediate 4 to 5

November 23rd



November 23rd CCP question was one of the more difficult ones and examined students' understanding of another acyl nucleophilic substitution-type reaction under acid-catalyzed reactions, but this time involving a carbohydrate glycoside as the starting material. This question involved a more intricate mechanism as students were required to recognize that this question was also a nucleophilic acyl substitution-like mechanism, however, unlike other CCP questions where the acyl group was already part of the starting material, this case required the acyl group to be formed initially prior to any substitutions being carried out. Of the 524 student sample, 81 students did not complete this CCP question, which left a total of 443 students in the question sample. A very small percentage of the class (0.02%) answered this question completely correct. One of the most common concepts lacking in this question was the indication of stereochemistry within intermediate 4 of the mechanism, illustrated in Figure 15, and the final product. Due to the configuration of the carbohydrate, nucleophilic acyl substitution can occur in two ways: nucleophile attack from the front or back of the anomeric carbon. The resulting hydroxyl group can either be in the equatorial or axial position depending on the position of attack. Of the students who obtained a wrong intermediate 4, 75.5% of those students got it wrong due to a lack of indication of stereochemistry. This suggests students did not know that indicating stereochemistry was necessary at this intermediate or they did not understand the concept of stereochemistry. However, further analysis indicates that 31.6% of students who did

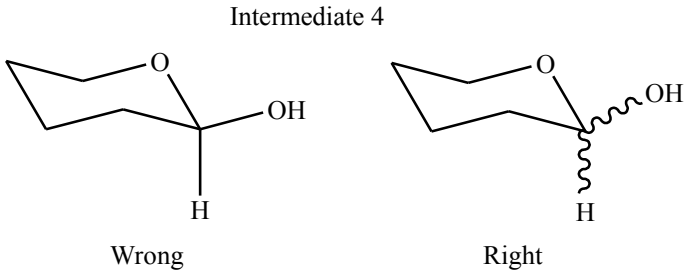


Figure 15. A common occurring error in November 23rd carbonless copy question: the lack of stereochemistry indication within intermediate 4 of mechanisms (squiggly lines represent that the substituent have unspecified stereochemistry, and will result in a racemic mixture)

not indicate stereochemistry in intermediate 4 had indicated the correct stereochemistry for their final product. This implies that this group of students understood stereochemistry, however, did not indicate it within intermediate 4. Another 12.1% of students maintained their lack of stereochemistry in their final product. The remaining students either did not have a final product because they did not reach that far in their mechanisms, or their products were considered wrong due to other sources of errors.

Within most of the CCP questions, there were frequent cases where no formal changes were indicated on the intermediates. However, if we focus our attention to the formal charge problem in this particular question, we may see more frequent instances of formal charge error as there are more opportunities. Figure 16 represents the amount of students lacking indication of formal charge across intermediates within the mechanism. Statistics drawn upon for this graph were based on number of intermediates attempted, in other words, students who did not draw the intermediate were not counted. In addition, Figure 16 shows an increase in incidences of the lack of formal charges as the mechanism progresses. Note that there was no incidences counted in intermediate 4 as it was not necessary to show any formal charges since it was a neutral molecule. After intermediate 4, there is another increase in no formal charge incidences. Another

trend found in this mechanism was that there was a decrease in number of intermediates attempted as the mechanism progressed. This question was one of the longer CCP questions students were asked to complete, and they might have ended the mechanism prematurely due to the level of difficulty of the question or not having enough time to complete the question.

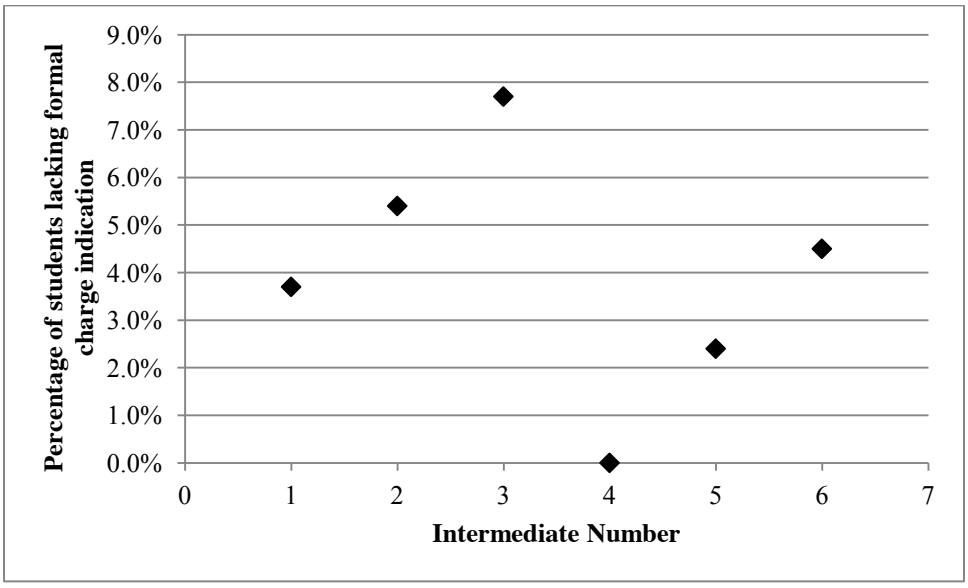


Figure 16. Percentage of students' work lacking formal charge indication based on number of attempted intermediates within November 23rd carbonless copy question

One other frequent error that is worth mentioning is the occurrence of a "wrong source, right end" point in a deprotonation step. Figure 17A and Figure 17B demonstrates examples of wrong arrow steps, while Figure 17C shows the correct electron movement from the O-H bond returning to the positively charged oxygen. This suggests that students either are misinterpreting what an arrow indicates (a movement of electrons from an atom with available lone pairs), did not have prior knowledge that hydrogen has no available lone pairs, or students just did not make the effort to distinguish the bond or the hydrogen to accurately portray what was happening. Whatever the case may be, this concept is worth a minor review in lecture to ensure students understand the proper protocol of the use of arrows for electron movement.

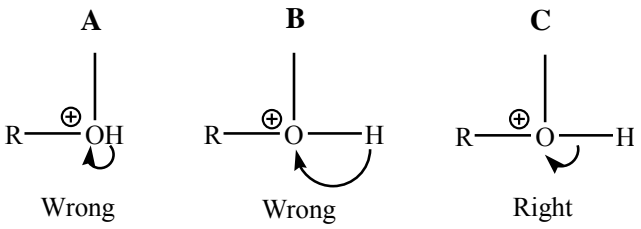
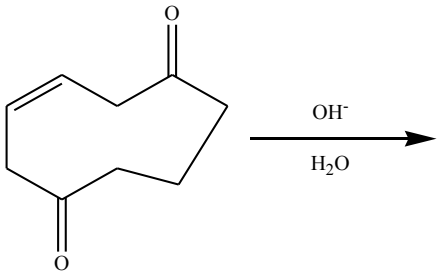


Figure 17. (A,B) Example of an arrow with wrong source and right end point (C) Example of an arrow with right source and right end point

November 30th



November 30th CCP question examined students' understanding of aldol condensation reactions involving basic conditions. Of the total 524 students, 107 students did not complete this CCP question which left a total of 417 students in the sample. A small percentage of the class who completed the CCP activity (12.2%) answered this question completely correct. One of the most common conceptual errors in this aldol condensation reaction is within the initial deprotonation step of the wrong α-hydrogen. An illustration of correct and incorrect deprotonation sites are shown in Figure 18. About 17.7% of students had deprotonated the wrong hydrogen, which usually lead to highly unlikely and unstable four and seven membered ring structures. This suggests that theses students do not fully understand the conditions that make certain α-hydrogen atoms more reactive than others. More focused review on reactivity of α-hydrogen atoms in certain environments, and the stability of cyclic structures should be considered to ensure students have the prior knowledge when approaching these types of questions and realize when they have approached a very unlikely product.

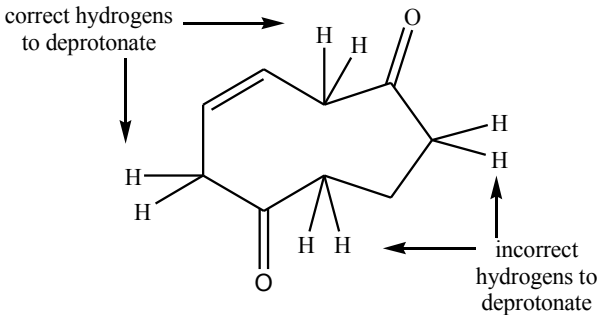


Figure 18. Four most common deprotonation sites of the starting material in November 30th carbonless copy paper question

Preliminary Analysis of Student Progress over Multiple Mechanism Questions

Electrophile activation. An initial analysis was performed on the concept of electrophile activation by initial protonation across four similar types of CCP questions including: October 26th, October 28th, November 9th, and November 23rd. The conditions given in these questions were acidic and each mechanism required an initial protonation step. Patterns of student performance on the initial protonation step were found through use of PivotTables shown in Figure 19. This shows all possible sixteen patterns students may have taken. The most popular pattern, taken by 32.0% of the class, was getting the initial protonation step wrong the first time, then right the next three times (shown in red of Figure 19). The second most common pattern occurring in 16.3% of the class, was getting the first three trials wrong, and then finally getting the last trial correct (shown in blue of Figure 19). Note that blank cells in excel from students who did not hand in a CCP or did not attend class were counted "wrong" in this case to make a more "pivot table friendly" data source. In addition, the performance of students in electrophile addition increased as more questions were completed, illustrated in Figure 20. For the graph, note that only students who completed the CCP were counted in this case.

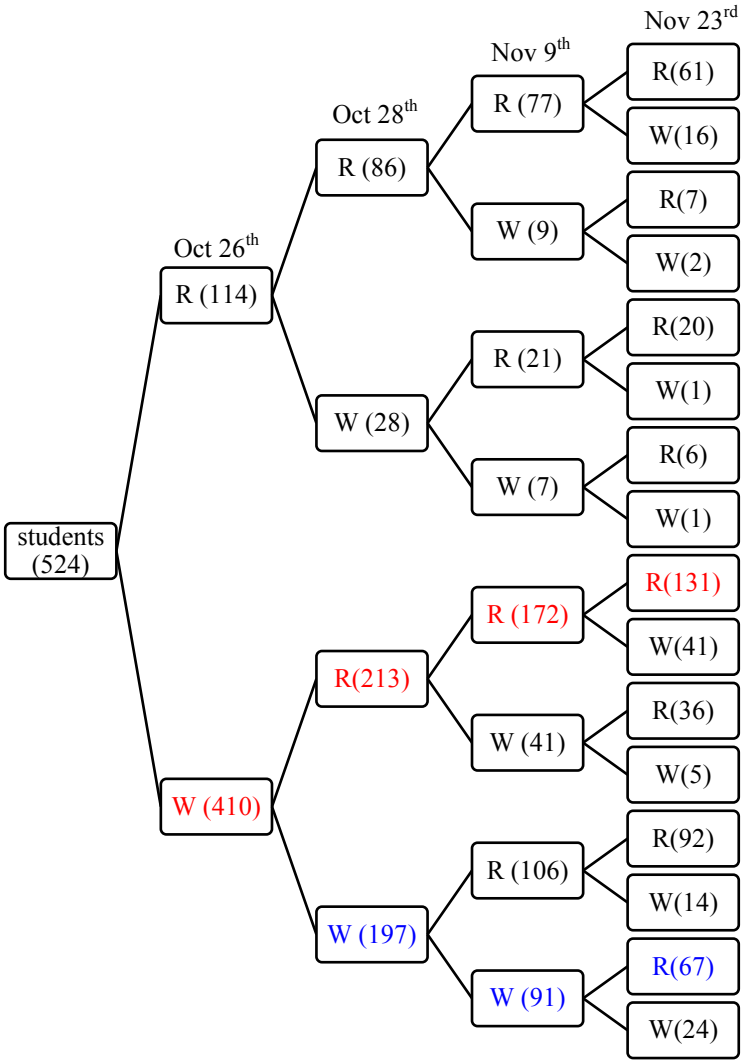


Figure 19. Results of initial protonation step across four carbonless copy questions (R=right, W=wrong, numbers in brackets represent number of students performing initial protonation correctly or incorrectly)

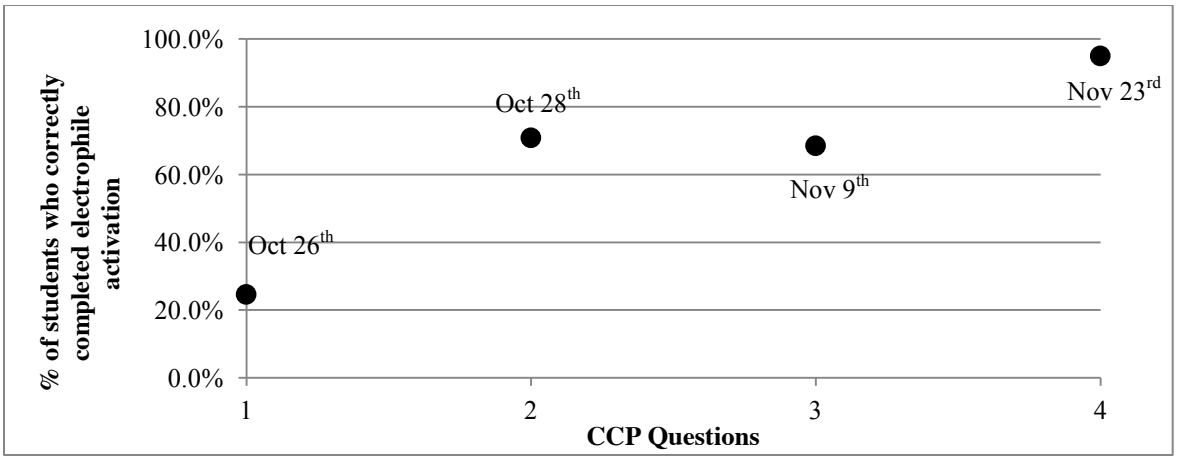


Figure 20. Performance of students in the activation of electrophile step across four similar questions

Limitations

A limitation to note in this study is that students may not have made their best efforts in answering the CCP questions. As motivation to do the activity, a participation mark was given for each CCP question. In order to receive a participation mark, students were required to use the CCP (not just regular paper), attempt the problem (not just write the problem down), and they must have written their name and student number in the top right corner of the page. For the "correction" page, students were required to make detailed corrections to their work, instead of simply writing out the correct answers below their work. If a student met all of the above criteria, they would receive a participation mark for the CCP activity of that day. Since students were not marked on how well they answered the questions, some students may not have attempted to answer the questions to the best of their abilities. Another limitation to this study was that it was difficult to compare across questions as students may have done more or less preparation before each CCP activity was done.

Conclusion & Future Studies

The goals of this exploratory study was to develop a practical method to interpret and organize the large amount of compiled data from the CCP instruction activity, as well as utilize the method constructed to analyze the most common conceptual errors within CCP questions. Pivot tables were the central tool of this project, and were utilized for essentially all the analyses. The findings of this study will serve to provide data on students' problem solving skills to inform future educational studies, curriculum designers, and instructional activity developers. Data from this study will also be utilized to formulate potential organic chemistry questions for an online prototype activity in hopes of helping students learn organic chemistry more effectively. Further studies can be carried out in the future to test the outcomes of paper and pen versus online based instructional activity.

Acknowledgments

I would like to thank the Research Team (Kelvin Choi, Mahailo Veljovic, Alexis Lee, and Victoria Bass) for their continued help and support throughout this exploratory study. It was with full dedication and teamwork of the Research Team that made this study possible. Special thanks to my project supervisor, Jackie Stewart, for all her generous support and guidance throughout my research.

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Butler, L. D., & Winne, H. P. (1995). Feedback and self-regulated learning: a theoretical synthesis. *American Educational Research Association, 65,* 245-281.

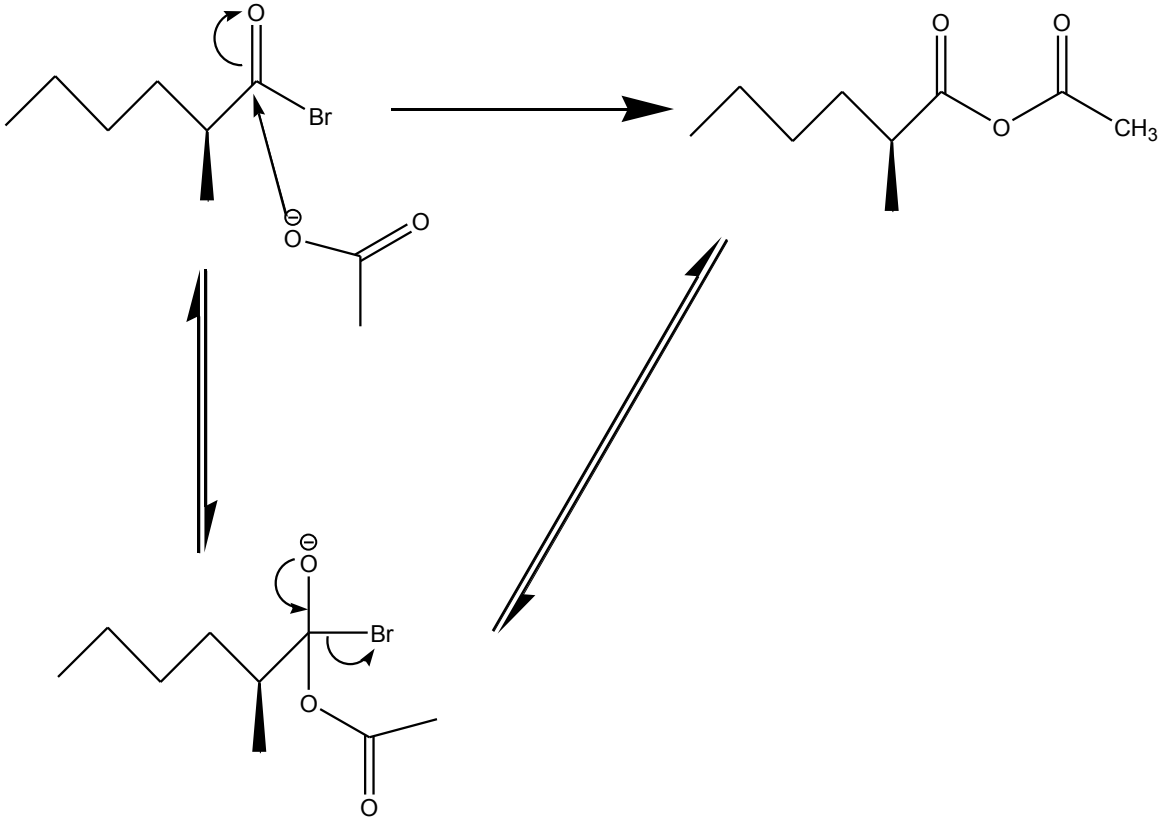
Ohlsson, S. (1996). Learning from performance errors. *American Psychological Association, 103,* 241-262.

Appendices

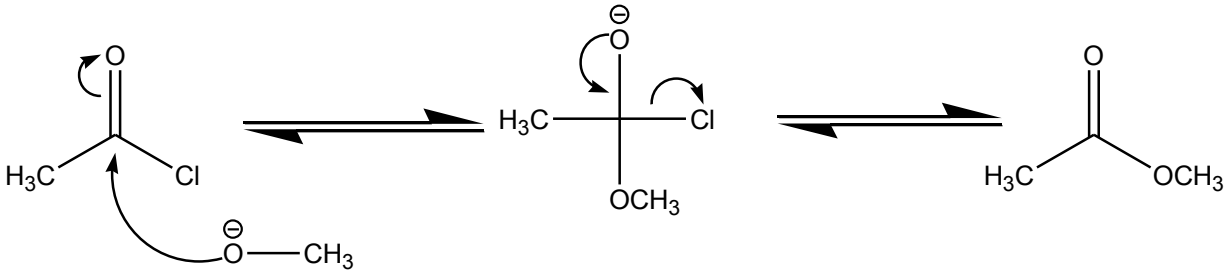
Appendix A

Answer key to CCP questions:

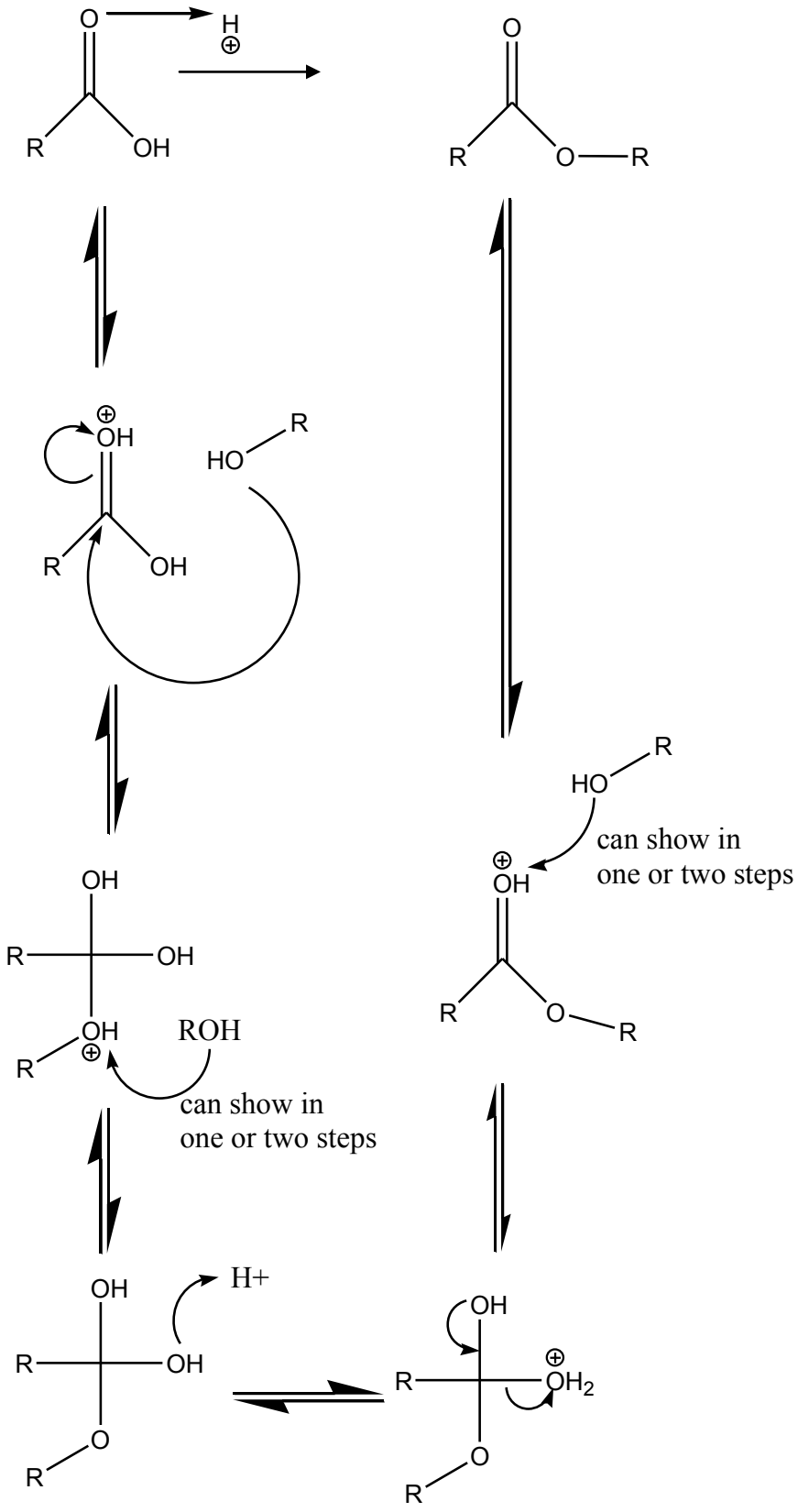
1) October 19th – Nucleophilic Acyl Substitution



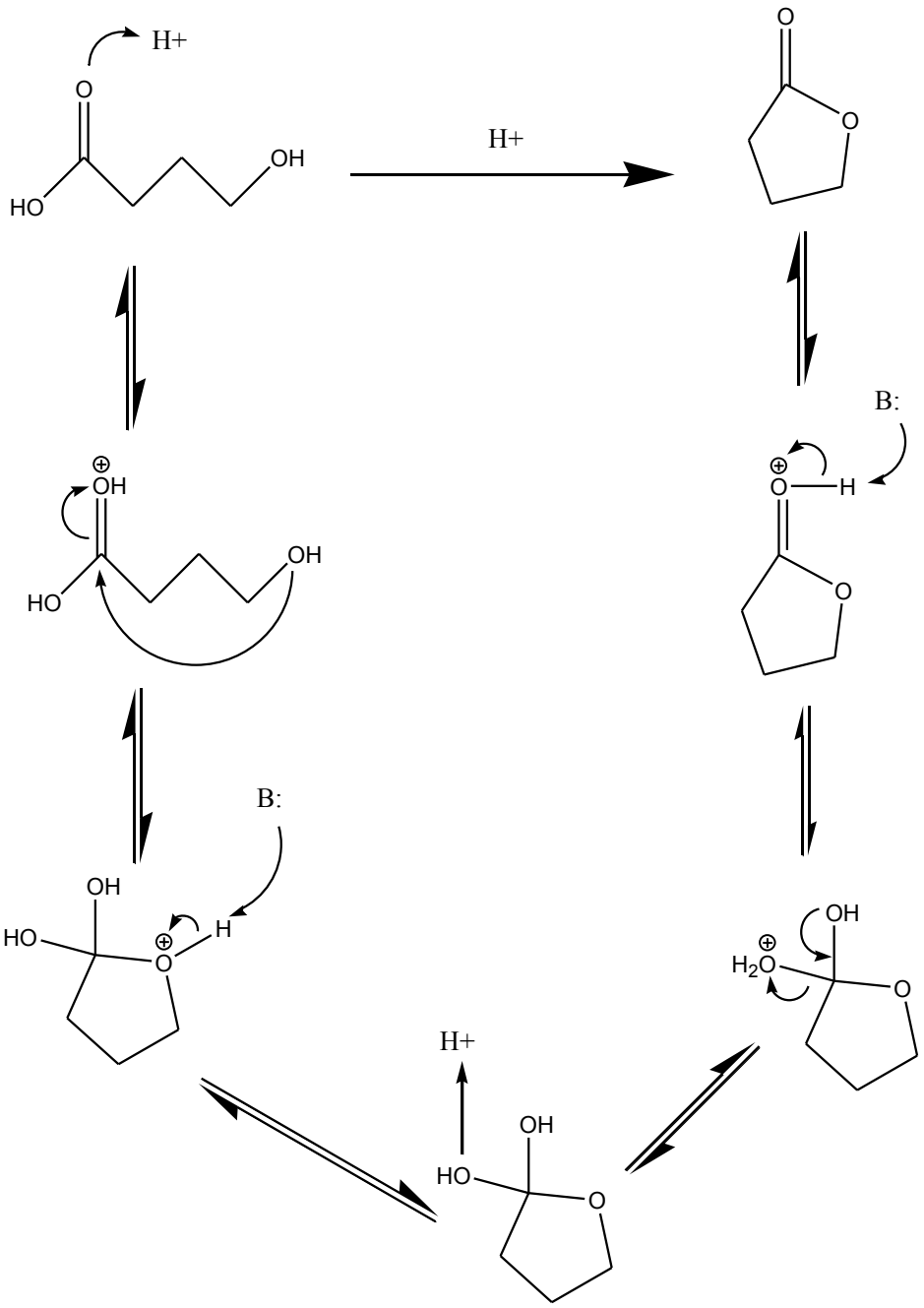
2) October 21st – Nucleophilic Acyl Substitution



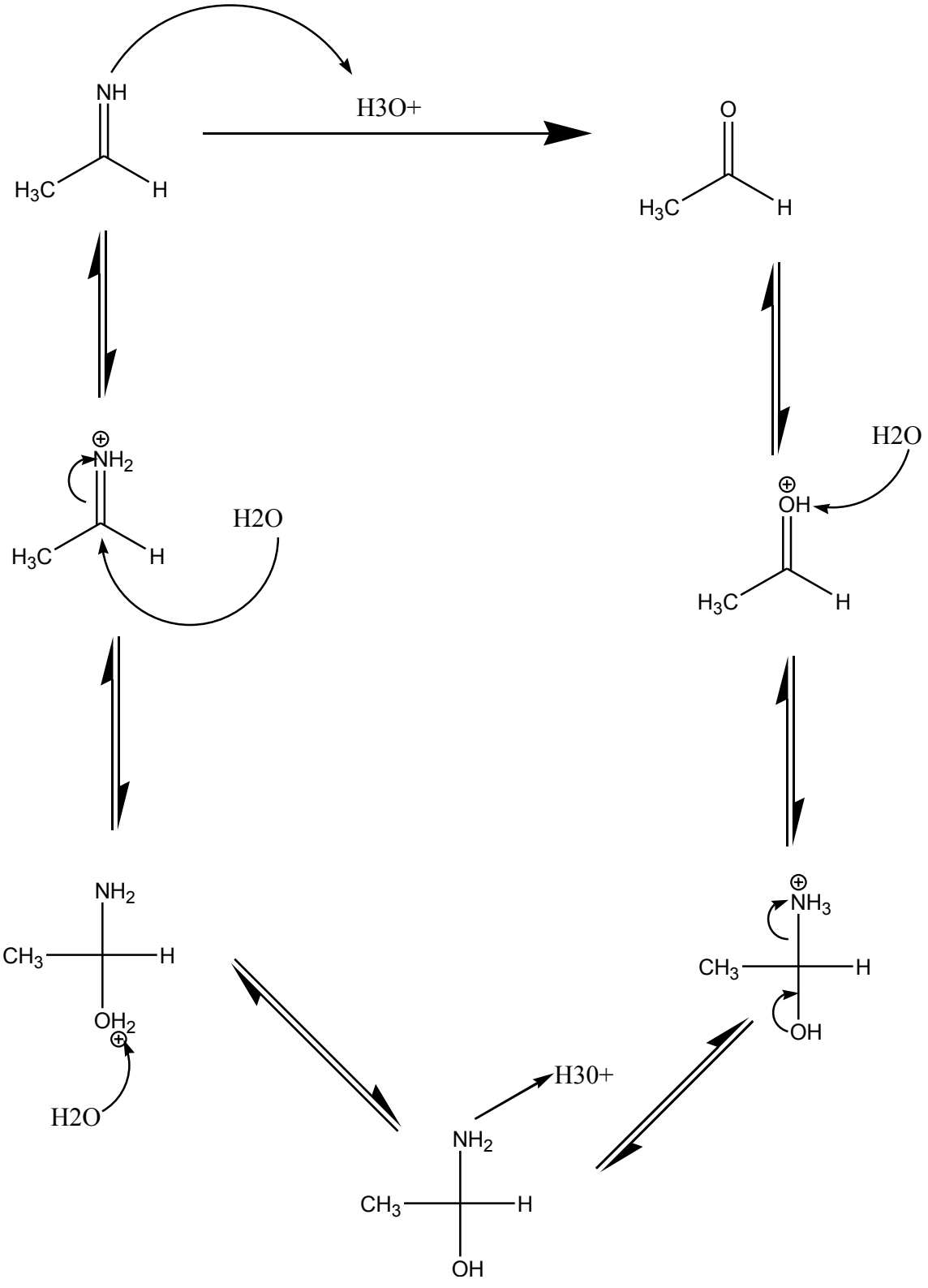
3) October 26th – Nucleophilic Acyl Substitution



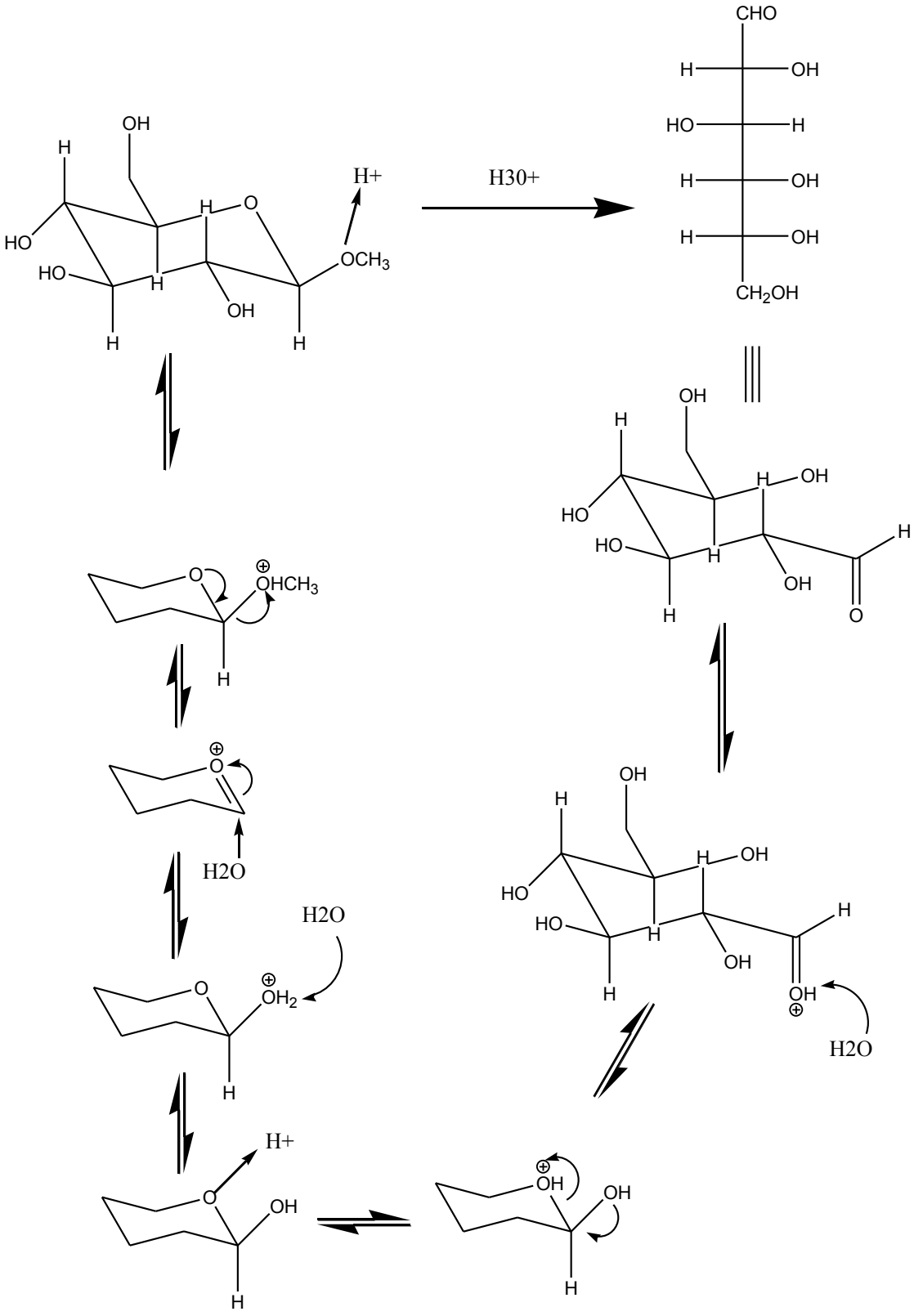
4) October 28th – Nucleophilic Acyl Substitution



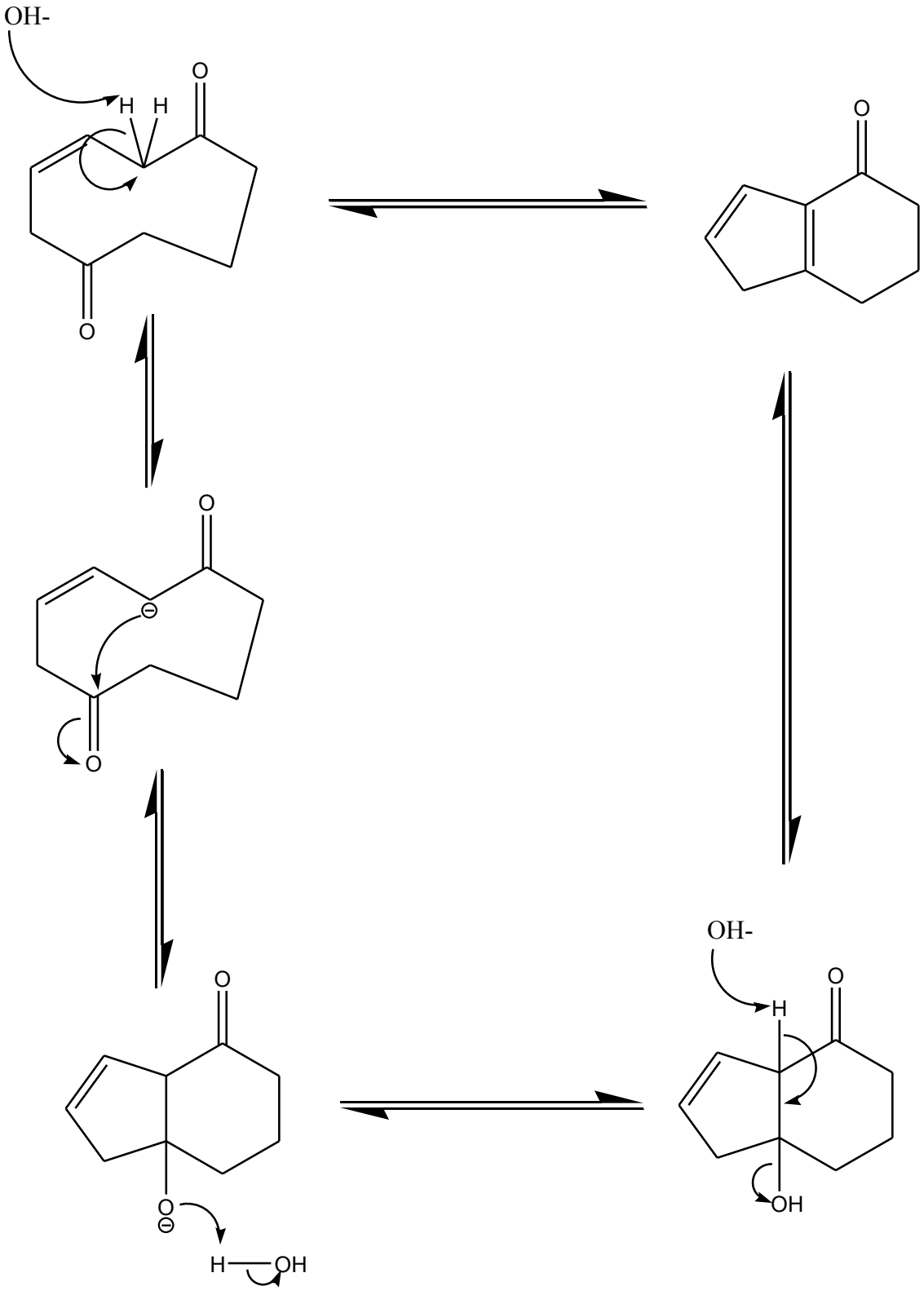
5) November 9th – Imine Hydrolysis



6) November 23rd – Acetal and Hemiacetal Hydrolysis



7) November 30th – Aldol Condensation



Appendix B

Sample coding scheme for October 19th CCP:

1st Step

Nucleophilic Structure:
Coded as:R/W/W(N.L.P)/W(N.D.)/A
R – Right
R(N.L.P) – Right, but no lone pair
W – Wrong
W(N.D.) – Wrong, no dissociation
W(NFC) – wrong, no formal charge
W(WFC) – wrong, wrong formal charge
A – Absent

e- Arrows x2:
(from nucleophile to acyl halide)
(from oxygen pi-bond to oxygen)
Coded as: RS/WS|RE/WE|A|B|WT
RS – Right Source
WS – Wrong Source
RE – Right End
WE – Wrong End
A – Absent
B – Backwards
WT – Wrong Time
-SN1 – LG leaves first, then nucleophile attacks later
-SN2 – has LG leave and nucleophile attacks simultaneously
-SPi – pi bond moves up to the oxygen by itself (not induced by nucleophile)

Points Given:
If both arrows have RS and RE
(0.5 x 2) / 1

Intermediate 1

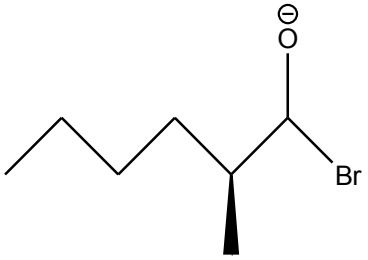
Coded as: R1/W(NFC)/W(WFC)/
W(BOR)/W(WSB)/W1/W2/W3/W4/W5/A/O

R1 – Correct Intermediate/product
W(NFC) –no formal charge
W(WFC) –wrong formal charge
W(BOR) –broken octet rule

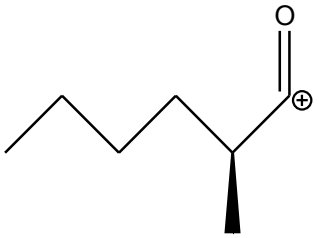
W(WSB) – wrong structural bonding
W1/W2/W3/W4/W5 – certain wrong intermediates, see below
A – Absent
O – Other

For intermediate 1:

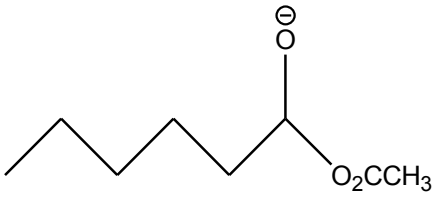
W1



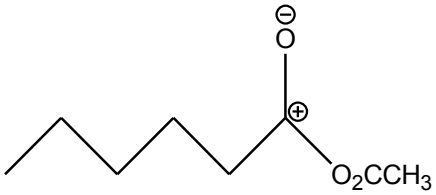
W2



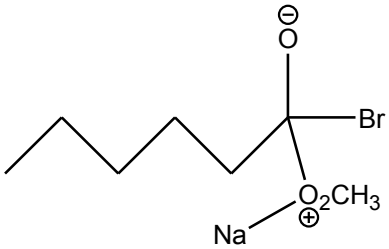
W3



W4

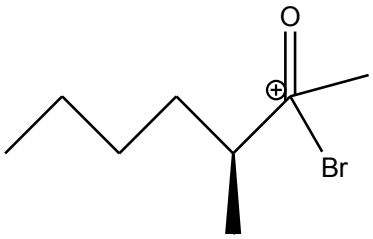


W5

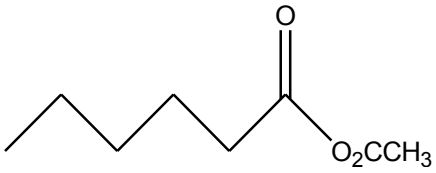


For final product:

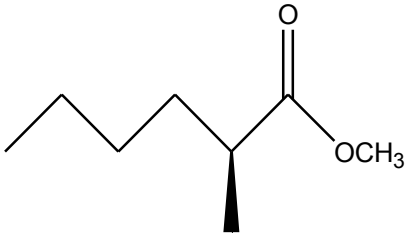
W1



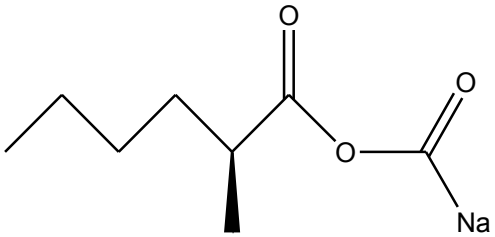
W2



W3



W4



Points Given:
Award 1/1 point for R1
Award 0.5/1 points for W(NFC1), W(WFC1), W(BOR1), 0 for anything else.

2nd Step

e- Arrows x2:
(from oxygen lone pair to pi-bond)
(from Bromine sigma bond to Bromine)

Same as 1st Step
Coded as: RS/WS|RE/WE|A|B|WT
RS – Right Source
WS – Wrong Source
RE – Right End
WE – Wrong End

A – Absent
B – Backwards

Points Given:
If both arrows have RS and RE (0.5 x 2)/1

Product

Coded as: R(CLS)/R(NLS)/W(WLS)/
W(WSB)/W(PFC)/W(DP)/A

R(CLS) – Right, with correct lewis structure
R(NLS) – Right, with no lewis structure
W(WLS) – Wrong, with wrong lewis structure
W(WSB) – Wrong, with wrong substituent bonding
W(PFC) – Wrong, with presence of formal charge (or incorrect formal charge if product is meant to have formal charge)
W(DP) – Wrong, different product
A – Absent

Points Given:
Award 1/1 for R(CLS) or R(NLS)
0/1 for anything else

CORRECTION CODES (For 2nd CCP)

For each cell
0= corrected mistake properly
2 = attempted to correct mistake but was wrong (incorrect correction)
Blank = was already correct (therefore, did not need to make a correction)

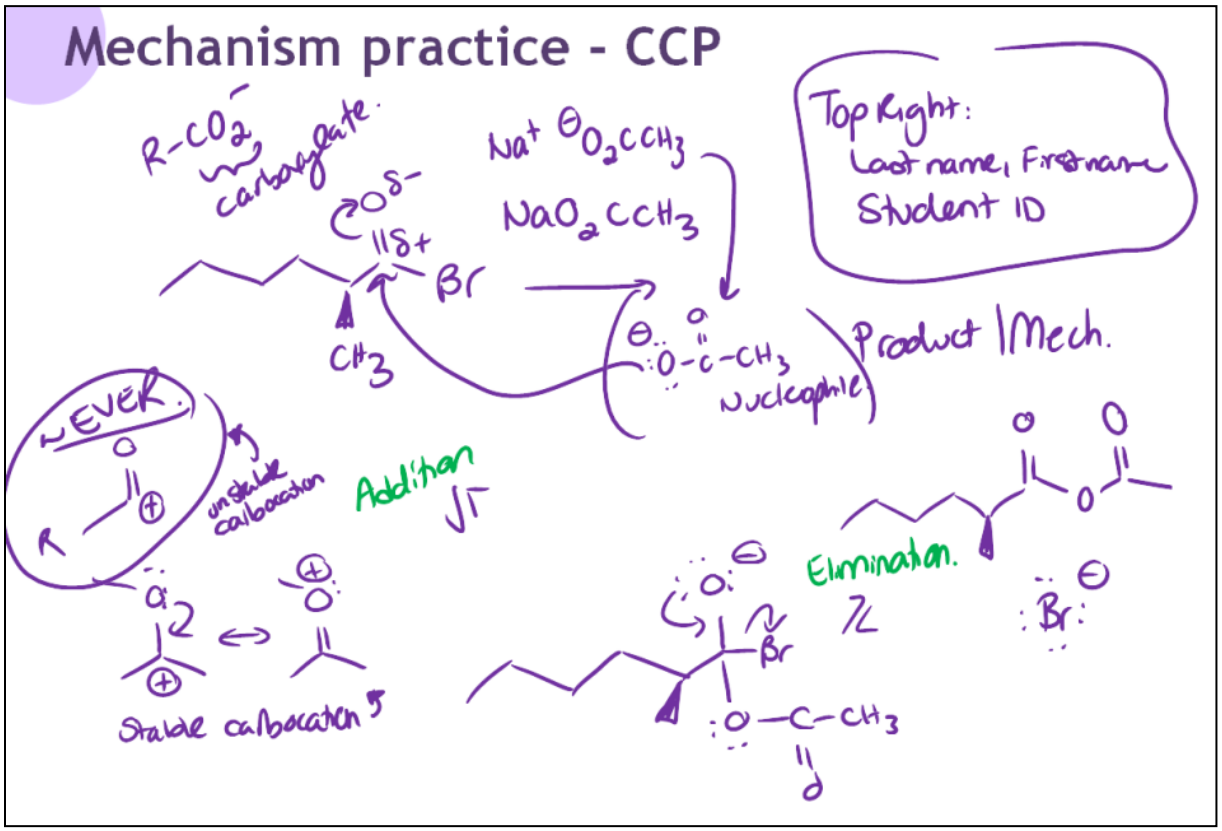
For entire question (written in "Comments" column)
C = correction completely correct
W = correction not entirely correct
NO = did nothing
C-No = did nothing but had correct mechanism to begin with
1 = corrected own work
2 = wrote out names of intermediates/nucleophiles/etc.
3 = wrote out the reasoning for at least one step (notes)
4 = rewrote the entire mechanism
5 = crossed out first attempt
6 = used different coloured pens
7 = used checkmarks and Xs to mark original work
8 = used PADPED (or parts of it)

*NOTE: When deciding whether to put 1 or 4:
-If they corrected more than 1 step of their mechanism, put 1.
-If they corrected 1 step or less, put 4.
-If they corrected more than 1 step of their mechanism, and then drew a completely new mechanism as well, put 1 AND 4.

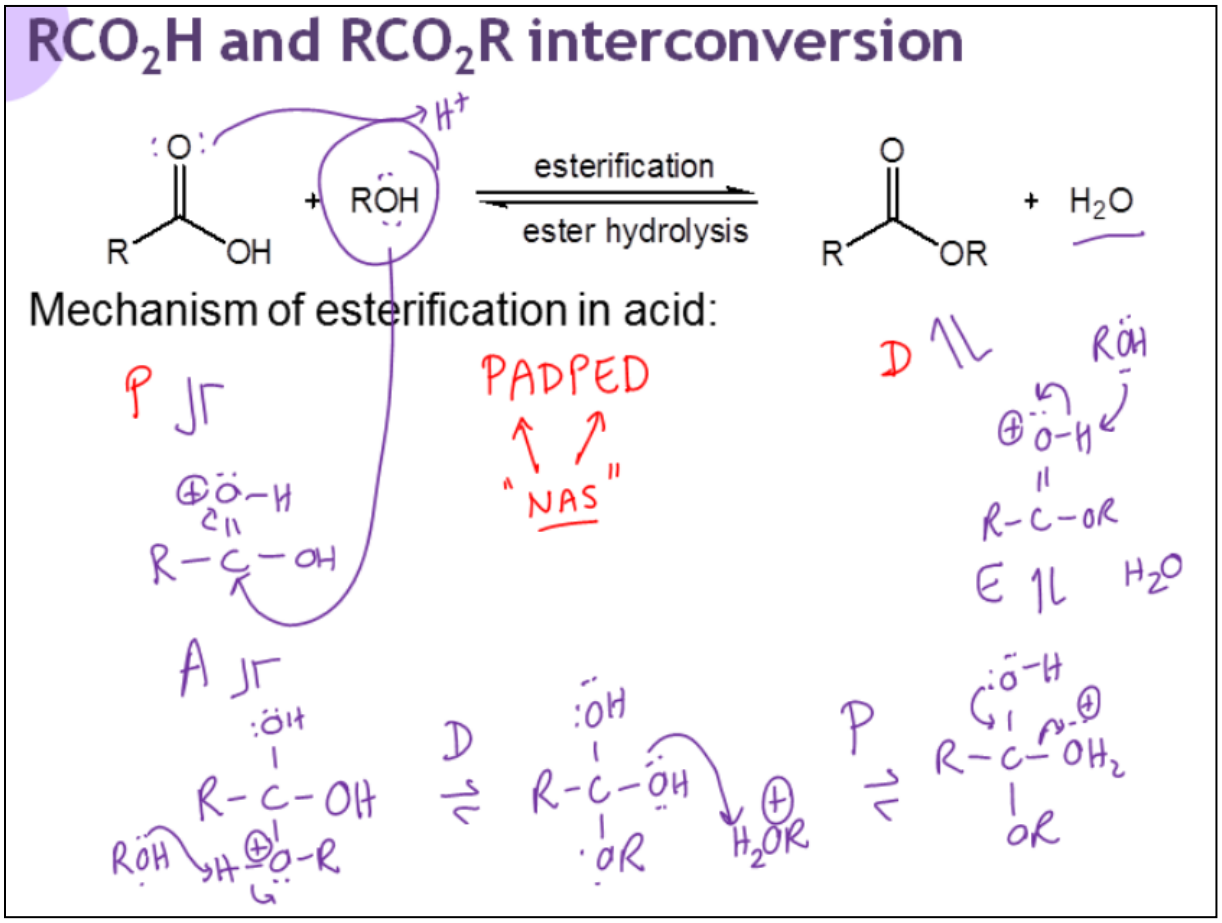
Appendix C

Sample in-class drawings of CCP answers:

1) October 19th – Nucleophilic Acyl Substitution



3) October 26th – Nucleophilic Acyl Substitution



6) November 23rd – Acetal and Hemiacetal Hydrolysis