Exploring students' initial interpretations of the electron-pushing formalism arrows

Denzel Huang

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Department of Chemistry and Biomolecular Science

Faculty of Science

University of Ottawa

Abstract

Chemists use the electron-pushing formalism to rationalize, analyze, and explain how a chemical reaction occurs on an electronic level. The electron pushing formalism (EPF) is the curved arrows representing electron movement. Some research on undergraduate organic chemistry students' understanding of the electron pushing formalism has presented evidence that some students do not find the electron-pushing formalism meaningful. Research at the University of Ottawa found that the EPF symbolism is meaningful to the participants because they interpret EPF arrows and use charges and mapping to problem-solve.

At the University of Ottawa, the organic chemistry curriculum was changed in 2012 to have students learn and interpret reactions based on similar reactivity patterns. The goal of the redesign was to give students the tools to analyze, predict, and explain how reactions occur instead of memorizing. An initial section of the curriculum is dedicated to teaching the electron-pushing formalism before any reaction. An exam analysis was conducted to see the new curriculum's effect by looking at students' drawn structures and EPF arrows. Students demonstrated minimal errors when drawing the EPF arrows and scored higher on familiar and unfamiliar reactions following the new curriculum, which suggests students found the EPF arrows meaningful. The following think-aloud interview study better captured student interpretations of the EPF arrows to determine what features students found relevant and whether the students who could explain a conceptual understanding of the EPF arrows could express a deeper understanding. The think-aloud interviews found that students do place meaning into organic chemistry representations as students were thinking about how to draw the EPF arrows based on prior knowledge. The data from the two previous studies were collected near the end of the course when students had a significant amount of experience, while students' initial interpretations of the EPF arrows are needed.

The primary focus of this thesis is to understand how students initially interpret the electron-pushing formalism arrows and look further into previous findings, which include electron movement, bond-forming and breaking processes, mapping, charges, stepwise reasoning, and transplanting electrons. Twelve students were recruited from Organic Chemistry I and interviewed over three weeks after being taught the electron-pushing formalism. The interviews were conducted using a think-aloud procedure to capture students' thoughts, and each interview lasted approximately 1 hour. The instrument consisted of six organic chemistry questions, specifically chosen, as students would not encounter them in the class and would have to interpret the

representations. The transcripts were analyzed with respect to the previous studies' findings and compared among participants to explore students' interpretations and use of the EPF arrows.

The findings from this study suggest participants found the EPF arrows meaningful because participants interpreted the representations as electron-movement, bond-forming, and bond-breaking processes which contrasts some prior research that reported students do not find the EPF arrows meaningful (Bhattacharyya and Bodner, 2005; Graulich, 2015). Participants connected the EPF arrows to electron movement, bond-forming, and bond-breaking processes. Participants compared surface features to determine how to draw the EPF arrows. Participants' visualization and how they approached the reactions differed. Participants' visualizations of the organic chemistry reaction were divided between a stepwise or concerted visualization. Most participants approached the EPF arrows stepwise as a problem-solving tool as it was easier for them to understand. Participants correctly interpreted most bond-breaking EPF arrows, but some participants relocated the electron pair onto a different atom instead of forming a bond. Participants mainly mapped the carbon atoms with numeric labels and found implicit atom-type questions challenging. Participants interpreted charges as an important surface feature and used charges to help them solve the question. Participants viewed charges as a reactive location where bonds break and form and compared the number of charges between reactants and products to check whether their answers were correct. The results suggest the participants in the study found the EPF arrows and made meaningful connections at the submicroscopic level with minimal experience.

Mastering the EPF arrows at the beginning of the course appears beneficial to student learning because participants interpreted the EPF arrows as a meaningful representation suggesting that the EPF arrows are less of a barrier when learning and mastering organic chemistry, under the University Of Ottawa's organic chemistry curriculum as intended. Since the EPF arrows are less of a barrier, students can focus on other organic chemistry concepts and can be more successful which is seen in the first exam analysis where minimal errors were seen. The first exam analysis observed minor pentavalent atoms and errors with the EPF arrows (Flynn and Featherstone, 2017). The following interview study found students described mapping, charges, stepwise, and chemistry reasoning when discussing electron movement (Galloway *et al.*, 2017). The findings from this work demonstrated the EPF arrows as a representation are meaningful to participants as they interpreted the EPF arrows after being recently taught. Similar findings at a different institution using a revised curriculum that focuses on the EPF at the beginning of the course found students were more likely to use the EPF arrows and were more likely to provide the

correct answer than their counterparts (Crandell *et al.*, 2018; Houchlei *et al.*, 2021). Research at institutions adopting the functional group curriculum reported that students did not find the EPF meaningful (Bhattacharyya and Bodner, 2005; Ferguson and Bodner, 2008; Grove, Cooper, and Rush, 2012). The findings suggest that the time spent mastering the EPF arrows at the beginning of the course is beneficial when learning organic chemistry because the symbols are less likely to be a hindrance through misinterpretation, and students can focus on mastering organic chemistry concepts.

Implications for teaching and learning include providing clarity on interpreting the EPF arrows and using the transplanting processes to demonstrate other chemical possibilities. Participants demonstrated comparing reactants and products when problem-solving. When students face difficulty, they should compare the products of chemical processes (bond-forming, bond-breaking, or electrons moving). The correct process has the EPF arrow starting from electrons and point to an atom or bond, maintains the conservation of atoms, and electrons stay with one of the originating atoms. The other processes will not follow one of the above principles, thus making them illogical.

Future work could further explore if students interpret the EPF arrows as a whole or if they interpret the arrowhead and arrow tail. Why do some students face difficulty keeping electrons on an originating atom? Why do some students face difficulty conserving atoms, electrons, and charges throughout a reaction? Whether the findings are generalizable by expanding the sample size.

In the context of the new curriculum, it appears students' have acquired a better understanding of the EPF. The results are promising because participants with minimal experience interpreted the EPF arrows and found them meaningful as a symbolic representation aligned with the curriculum's intentions.

Keywords: Chemistry Education Research, Organic Chemistry, Electron-Pushing Formalism, Language of Mechanisms, Problem-solving.

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In Loving Memory Of

Chester ChosenBun Bunnington

June 2019 — September 12th, 2021

Although our time was short,

you left the world better than you found it.

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List of Abbreviations

Abbreviation	**Expanded**
CHM (1301 or 1311)	Principles of Chemistry
CHM 1321	Organic Chemistry I
CHM 2120	Organic Chemistry II
EPF	Electron-pushing formalism
FRG	Flynn Research Group
H^+	Proton
IPT	Information Processing Theory
IUPAC	International Union of Pure and Applied Chemistry
REB	Research Ethics Board
S_N2	Substitution Nucleophilic Bimolecular
TF	Theoretical Framework

Chapter 1: Introduction and Literature Review

Section 1.1: Importance of representations in science

Scientists use representations to organize and illustrate data, where the primary purpose of a representation is to communicate scientific phenomena. Scientists commonly use visual representations, which require the receiver to make sense of the representation (Daniel *et al.*, 2018). Representations act as a bridge to connect the observer to the scientific phenomenon (Wellington and Osborne, 2001), with the quality of the representation affecting the ease of interpretation (Chi *et al.*, 1981). Representations intend to make learning phenomena easier to understand, but each representation has limitations (Wellington and Osborne, 2001). Although representations are designed to be helpful, representations can also be misunderstood, leading to misconceptions (Kozma and Gilbert, 2005; Daniel *et al.*, 2018). If students continue to develop misconceptions, students may face difficulty when gaining expertise (Daniel *et al.*, 2018).

Section 1.2: Internal and external representations

Representations exist in two forms: external and internal representations (Kozma and Gilbert, 2005; Opfermann *et al.*, 2017; Daniel *et al.*, 2018). An external representation can be perceived visually, such as a graph or a model (Opfermann *et al.*, 2017; Daniel *et al.*, 2018). The learner creates an internal representation in their mind to manifest the external representation (Opfermann *et al.*, 2017; Daniel *et al.*, 2018).

For example, an external representation can be a Rubik's cube perceived visually as a 3x3x3 cube that can rotate and turn with visual colours. An internal representation of the Rubik's could start as a singular cube with additional cubes added, eventually forming the 3x3x3 cube. The internal representation suits the user's needs, such as a mental rotation of the Rubick's cube. The Rubick's cube can be solved when the learner gains enough time and experience.

Section 1.3: Representational competence

The ability to create, communicate, interact, and understand representations will always be a critical aspect of science as representations effectively communicate scientific phenomena. Thus, understanding how students interact and understand representations is crucial for science education (Daniel *et al.*, 2018). Representational competence is interacting, making sense of, and communicating external representations (Kozma and Gilbert, 2005; Daniel *et al.*, 2018). Gaining representational competency takes time as learners need to interpret, interact, and understand external representations (Daniel *et al.*, 2018). When learners become competent and make better connections with external representations, they can mould their internal representation to suit their needs (Daniel *et al.*, 2018). Making connections between representations and scientific phenomena is critical in science education. Research has shown students in math and chemistry struggle when interpreting multiple representations as students would focus on a singular representation and abandon the rest (Ainsworth *et al.*, 2002; Gkitzia *et al.*, 2020).

Section 1.4: Chemistry language and representational competence in chemistry

In addition, learning the language and representations in chemistry has been referred to as learning a foreign language (Taskin *et al.*, 2017). Chemistry uses a complex vocabulary where slight changes in words indicate different representations (e.g. alkane, alkene, and alkyne). The language of chemistry also uses symbols to represent various things, such as pH, PH, and Ph, as potential hydrogen, phosphorus & hydrogen, and phenyl, respectively (Galloway *et al.*, 2017). Due to the multitude of symbols representing different chemistry concepts, novices described feeling like they were learning a new language (Talanquer, 2011; Taber, 2013; Markic and Childs, 2016). Learning the language has been reported as a major barrier when learning science or chemistry (Wellington and Osborne, 2001; Markic and Childs, 2016).

Organic chemistry uses a variety of symbols as part of the language to depict chemical phenomena which may contribute to the discipline's difficulty (Ferk *et al.*, 2003; Kozma and Gilbert, 2005; Gilbert and Treagust, 2009). Representations also act as a barrier because novices can interpret the representations as meaningless "letters, numbers, and lines" (Treagust *et al.*, 2003). Becoming proficient in chemistry is not a simple task, as understanding the language of chemistry can be challenging (Johnstone, 1991; Talanquer, 2011; Taber, 2013). In addition to the terminology being a major barrier when learning science or chemistry, learners need to connect scientific phenomena to the representations (Wellington and Osborne, 2001; Markic and Childs, 2016).

Researchers have found that even with a educator explaining chemistry representations and their concepts, some participants did not understand the purpose of the chemistry representations (Treagust *et al.*, 2003). Other researchers found that successful problem solvers in chemistry used representations to describe or characterize an idea, while unsuccessful problem solvers spoke or verbally wrote out their ideas (Bodner and Domin, 2000). The successful problem solvers interacted with their drawn representations, and when new information was available, they considered the new information as a representation (Bodner and Domin, 2000).

A review of studies that looked at students' understanding of organic chemistry representations found students often memorized the EPF arrows. Some students used rules (e.g. "nucleophiles attack electrophiles), allowing the reproducibility of EPF arrows without a complete understanding. Other students faced difficulties applying declarative knowledge, suggesting that the EPF arrows are only meaningful to previously learned reactions and decorated new reactions with the previously memorized EPF arrows (Graulich, 2015). Researchers investigated students' rationale when answering questions on organic chemistry exams (Anderson and Bodner, 2008). Seven students were all enrolled in a two-semester organic chemistry course at the undergraduate level. One participant, Parker, was used as a case study as their experience in organic chemistry was thought to be common. Parker was successful in general chemistry but was not as successful in organic chemistry. Interviews were conducted throughout the two semesters. However, Parker only enrolled in the first semester. During the first interview, Parker was initially enthusiastic and confident in his chemistry knowledge. Parker displayed discomfort in the second interview as he could not grasp the material presented. The discomfort Parker faced revolved around using chemistry symbols. Parker had trouble regarding line structures, translating 2D images into 3D images and interpreting the EPF, and explicitly described preferring answering sentence questions over symbolic ones. Parker drew two pentavalent carbons regarding line structures and could not differentiate between them. The line structure errors intrigued the authors to ask the class the difference between two structures, where participants indicated difficulty due to applying conscious effort to interpret the structures correctly. When Parker looked at 2D chair structures to predict stability, he discussed chemistry concepts, but his inability to translate 2D structures into a 3D image limited him. Parker reached the electron-pushing formalism section of the course and faced difficulties as he could not understand the purpose of the electron-pushing formalism arrows. The purpose of the EPF arrows was made clear in the lectures, but the electron-pushing formalism arrows were not a valid reason for Parker as an explanation of chemical phenomena. The authors believe that Parker could not connect the symbols used with chemistry concepts, and thus the symbols were meaningless to Parker. Anderson and Bodner's work suggests learners need to take the time and effort to connect the representations to concepts for the representations to become meaningful.

Researchers in Croatia investigated undergraduate and graduate students' understanding of chemistry words and representations (N = 82 and 36 respectively) (Vladušić *et al.*, 2016). The researchers created a four-part instrument to examine students' knowledge of scientific and non-scientific words, including Croatian words. Participants found defining scientific terms and writing scientific words in a sentence a challenge. Both undergraduates and graduate participants misinterpreted some terms, with the researchers rationalizing the misinterpretation as a language barrier. For example, participants would misinterpret "carbonization" with "caramelization," "coefficient" with "quotient," or "faction" with "fracture." The researchers described their participants found defining symbols challenging. Most participants correctly defined the less than symbol but found it challenging when defining chemistry terms such as orbitals. The results suggested that their participants have an inadequate understanding of scientific terms and representations, regardless of the task. The study had limitations as the authors expected the students to perform a certain way when not explicitly asked, and similarities between Croatian and English words led to errors.

Researchers investigated students' interpretations of the representations used in acid and base reactions in organic chemistry (Cartrette and Mayo, 2011). Fourteen students were recruited from two sections of organic chemistry with different professors teaching the course. Interviews were conducted using a think-aloud procedure and lasted for approximately one hour. The interview started with general acid and base questions to gauge students' understanding and finished with problem-solving acid and base questions. All participants responded to an open-ended question, "what is an acid?" using the Brønsted-Lowry acid and base theory. The participants described acids as a species with an available proton (H^+) and bases as a species that accepts the proton (H^+). The concept of Lewis acid and base theory was only discussed when asked. When probed about Lewis theory, the participants' understanding was minimal as some participants did not know Lewis theory existed. The participants' definitions of acids and bases were based on a surface feature of whether a proton (H+) was available to be donated. The emphasis on protons might be due to the previous general chemistry course, which spent four weeks on Brønsted-Lowry theory and only two hours on Lewis theory. The interviewer asked participants to define the terms electrophile and nucleophile. Twelve participants correctly defined the terms, with eight of those participants connecting supporting information such as charges, electrons, nucleophiles, and electrophiles. The interviewer directly asked participants if there were any connections between nucleophiles and electrophiles to acids and bases. Four participants connected nucleophiles to electron donors (Lewis base), while the remaining participants did not describe any meaningful connections. The authors suggest the lack of connections was due to the participants' reliance on Brønsted-Lowry theory even when it was irrelevant and often led to a forced answer. The authors rationalize the reliance on Brønsted-Lowry theory because high school and general chemistry emphasize Brønsted-Lowry theory. The study revealed participants focused on protons (H^+) as a representational shortcut to determine whether the molecule was an acid or base.

Researchers investigated students' interpretation of nucleophiles and electrophiles in organic chemistry (Anzovino and Bretz, 2015). Participants (N = 11) were recruited and interviewed halfway through the second semester of organic chemistry Interviews lasted approximately 60 minutes, where a Livescribe smartpen recorded audio and penmanship. Participants were taught the reactions in the lectures, emphasizing the distinction between nucleophiles and Bronsted-Lowry theory, including the electron-pushing formalism arrows before the interview. Participants used surface features, such as charges, to determine whether the molecule was a nucleophile or an electrophile. The surface features include whether the atom has an electron pair, while other participants used charges. Participants described a negative charge as a nucleophile and a positive as an electrophile. The participants described an understanding of nucleophiles and electrophiles, but the results indicated a lack of understanding because participants incorrectly applied their definitions. Due to the small sample size, the results should not be used to generalize. However, the study provides further evidence that students need to connect representations to concepts.

In addition to the language used in chemistry, students in organic chemistry need to learn the representations and the concepts behind them. Until the representations become meaningful to the learner, the representations will likely stay as meaningless "letters, numbers, and lines" (Treagust *et al.*, 2003). This work looks further into studets' interpretations of the eletron-pushing formalism as a representation.

Section 1.5: The electron-pushing formalism

Organic chemistry uses curved arrows, the electron-pushing formalism (EPF), as an essential representation of describing how bonds are formed or broken via curved arrows that represent electron movement (Galloway *et al.*, 2017). The EPF is a tool chemists use to explain, predict, and communicate how a reaction occurs (Grove, Cooper, and Rush, 2012; Bhattacharyya, 2013; Galloway *et al.*, 2017). However, research suggests participants find the EPF arrows challenging to understand (Bhattacharyya and Bodner, 2005; Ferguson and Bodner, 2008; Grove, Cooper, and Rush, 2012). Students need to gain proficiency in using the EPF arrows as representations and interpreting the EPF arrows. EPF arrows must be drawn from a pair of electrons and point to either a bond or an atom to depict bond-forming and breaking processes (Flynn and Ogilvie, 2015). Until students see the benefit of using the EPF arrows, the EPF arrows are meaningless representations (Graulich, 2015).

Researchers investigated how graduate chemistry students draw EPF arrows (Bhattacharyya & Bodner, 2005). Think-aloud interviews were conducted with fourteen postgraduate students in several chemistry disciplines. Interviews consisted of nine EPF questions and a practice exercise. All participants correctly produced the mechanism for the warm-up question; however, they could not explain the steps when asked. Their inability to explain the steps suggests the participants may not understand the underlying chemistry concepts. The participants heavily focused on the starting materials, intermediates, and products, rather than understanding the processes used to convert them. The participants' focus on the molecules led them to propose incorrect EPF arrows. These incorrect EPF arrows resulted in intermediates that were unlikely to form. When discussing the EPF arrows, a common response was, *"it gets me to the product,"* indicating most students did not find the EPF arrows meaningful. The authors believe the inability to connect the EPF arrows as a process that transforms reactants to products contributes to the students' lack of understanding of the EPF arrows.

Similar research investigated how undergraduate chemistry majors draw EPF arrows (Ferguson and Bodner, 2008). Sixteen students enrolled in a two-semester organic chemistry course that explicitly taught the EPF arrows were interviewed. Interviews were conducted at the end of the second semester to maximize the course material provided. Interviews consisted of seven questions regarding the electron-pushing formalism. The authors described their participants had generally adhered to the EPF arrow rules, such as source-to-sink. The source-to-sink rule describes two electrons moving from an electron-rich source to an electron-deficient sink. The participants connected the EPF arrows to several chemistry concepts like acid and bases, electronegativity, and stability. However, the EPF arrows appeared meaningless to the participants. Participants viewed proposing EPF arrows as an academic exercise instead of a problem-solving tool and only drew the EPF arrows when asked. When proposing EPF arrows, some participants could not remember or partially remember the appropriate chemistry concepts involved, resulting in confusion. Participants continued to rely on their memory instead of trying to solve the problem. Half of the participants acknowledged they thought the EPF arrows were meaningless and a mental exercise. The authors suggested emphasizing the importance of the EPF arrows and explicitly demonstrating the connection between the symbols and the concepts they represent when teaching.

Researchers investigated undergraduate students' interpretation of the EPF arrows (Grove, Cooper, and Cox, 2012). The study involved 399 students enrolled in three sections of a second-semester organic chemistry course . Participants proposed EPF arrows and products for six organic chemistry reactions three weeks before the semester ended. The participants were familiar with the first four reactions and unfamiliar with the last two, which required an application of organic chemistry knowledge. Responses were collected while the participants were on break during their laboratory sessions. There was no significant difference between participants who proposed mechanisms and those who did not propose mechanisms for the familiar questions. Participants who proposed mechanisms for the unfamiliar questions were more successful. However, the success rate was low and was reasoned to be due to the difficulty of the questions. The authors suggest that understanding the EPF may be a barrier when understanding organic chemistry, and students must develop an understanding of the EPF to succeed in organic chemistry.

Researchers investigated how students develop their skills regarding EPF arrows in organic chemistry over a given period (Grove, Cooper, and Rush, 2012). Participants (N = 300) enrolled in a two-semester, second-year organic chemistry course were recruited from three lecture sections with different instructors. Participants were asked four times over two semesters to answer an increasing amount of organic chemistry questions. Participants completed the assessment mid-way through the semesters and at the end of the semesters. The questions asked participants to propose EPF arrows and draw the associated product. The researchers found most participants did not engage in the activity or drew the EPF arrows after determining the product, demonstrating students do not view the EPF arrows as a problem-solving tool.

Researchers investigated what effects an online preparatory course for organic chemistry had on students interpretations of organic chemistry reactions (Fischer *et al.*, 2019). The study was quantitative, with 1289 participants enrolled in organic chemistry. The online preparatory course was 16 video podcasts that focused on Lewis structures, resonance structures, and the EPF. The results from the study show that participants benefited from using the online course because participants' grades were higher in the subsequent organic chemistry course compared to their previous organic chemistry course. The study demonstrates that students require time and experience with the EPF for the symbols to become meaningful.

Multiple research studies have presented how students do not find the EPF arrows meaningful (Bhattacharyya and Bodner, 2005; Anderson and Bodner, 2008; Ferguson and

Bodner, 2008; Kraft *et al.*, 2010; Grove, Cooper, and Rush, 2012). When students draw EPF arrows, studies found students proposed illogical EPF arrows (Zotos et al., 2021), proposed EPF arrows after determining the product (Grove, Cooper, and Rush, 2012), chose not to provide EPF arrows for a known reaction (Houchlei *et al.*, 2021), or memorized the EPF arrows for the task or a previously learned reaction (Grove, Cooper, and Rush, 2012). When determining if students interpret the EPF arrows, studies found some undergraduates thought the EPF arrows were an academic exercise instead of a problem-solving tool (Ferguson and Bodner, 2008), EPF arrows are equivalent to “plug-and-chug” (Bhattacharyya, 2014), or EPF arrows are not a valid explanation for why a chemical reaction occurs (Anderson and Bodner, 2008), demonstrating the students did not interpret the EPF arrows.

The results of the previously described EPF arrow research recommends that the EPF arrows have to be meaningful to students for students to benefit from the EPF arrows. In addition, learners need time and experience to gain expertise. Students who approached the EPF arrows systematically and organized were more successful (Grove, Cooper, and Rush, 2012). Alternatively, a study using inaccurate bouncing curved arrows instead of the traditional EPF arrows helped students build a conceptual understanding of a bond-forming (Straumanis and Ruder, 2009). Although the differences in the studies representing students finding meaning in the EPF are not known, this thesis attempts to understand what meaning students are placing on the electron-pushing formalism arrows starting with the curriculum.

Section 1.6: Curriculum redesign

Organic chemistry is a field of chemistry existing less than 200 years (Giunta, 2010). Originally, chemical tests determined the existence of a functional group, leading to the characterization of compounds (Giunta, 2010). In 1922, Kermack and Robinson included the movement of electrons in reactivity when only atoms were considered previously (Kermack and Robinson, 1922). The movement of electrons was represented as curved arrows, which we refer to as the EPF arrows. The EPF arrows have proven to be a powerful tool chemists use to explain why reactions occur when previously unknown and predict the outcome of new reactions. Although there has been an advancement in the field, the curriculum and textbooks did not change. The organic chemistry curriculum naturally followed the functional group approach, which promoted memorization without understanding the material, requiring extensive time and experience to gain proficiency.

At the University of Ottawa, a curriculum redesign for organic chemistry was implemented in January 2012 to improve the curriculum based on prior research (Flynn and Ogilvie, 2015). The goal of the curriculum redesign, Organic Chemistry I and II (CHM 1321 & CHM 2120), was to improve student learning and abilities when solving organic chemistry reactions. The redesigned curriculum emphasizes reactivity patterns and similarities between mechanisms, which reduces the need to memorize reactions as students learn why organic reactions occur through logical steps. Under the new curriculum, students are taught the electron-pushing formalism arrows before learning reactions to promote fluency in the EPF arrows. Thus, an early section of the course is dedicated to students becoming comfortable and fluent when interpreting and explaining the EPF arrows. When reactions are taught, the reactions are organized and introduced through similar mechanistic steps. The implemented curriculum started in January 2012 with Organic Chemistry I, where instructors found the curriculum to be straightforward, and students' responses were positive (Flynn and Ogilvie, 2015).

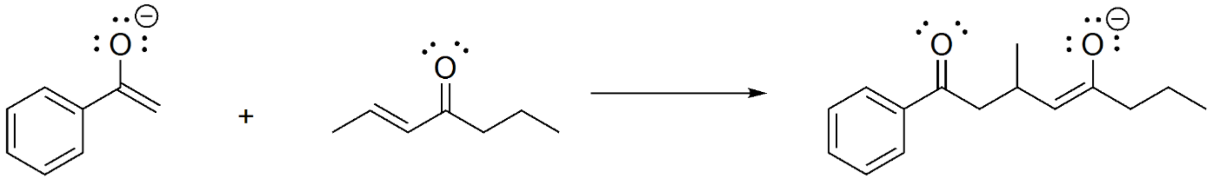
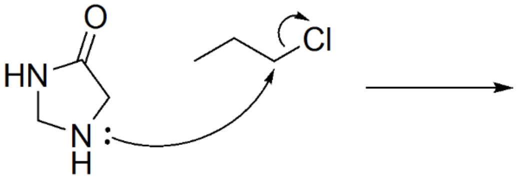
It is intended that students will achieve four learning outcomes related to the EPF representations by the end of the Organic Mechanisms Mastering the arrows module (Flynn *et al.*, 2016). Students will be able to 1) draw the product of a single mechanistic step given the starting materials and EPF arrows, 2) draw the EPF arrows given the starting material and products of a step, 3) draw the transition state structure for a reaction, and 4) draw the reverse reaction mechanism, given the elementary steps in the forward direction. The learning outcomes are designed for students to gain fluency and master the EPF arrows before learning reactions.

Section 1.7: Flynn research group studies

This thesis follows two previous studies conducted by the Flynn research group (FRG) looked at student understanding of the EPF arrows by using specific questions (Flynn and Featherstone, 2017; Galloway *et al.*, 2017). The questions were chosen from reactions that students had not yet learned, meaning students would have to interpret the EPF arrows. An exam analysis was performed to see the effect of the new curriculum. The exam analysis found minimal errors, suggesting that the EPF arrows are meaning to students, but was limited to the writing on paper and students' interpretations of the EPF arrows are still unknown.

In the first exam analysis, the researchers explored how the redesigned organic chemistry curriculum affected student learning (Flynn and Featherstone, 2017). The researchers investigated two learning outcomes: 1) draw the EPF arrows given the reactants and products, and 2) draw the products given the reactants and EPF arrows (Table 1). The researchers addressed the first learning outcome by analyzing the draw the EPF arrow type questions when provided the reactants and products. The researchers addressed the second learning outcome by analyzing the draw the product type questions, where reactants and EPF arrows were provided. The researchers chose specific reactions that students would not be familiar with to examine students' interpretations of the EPF arrows as a representation.

Table 1. Examples of drawing the arrow and drawing the product type questions.

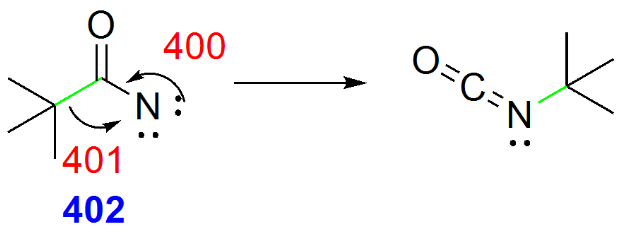
1. Draw the EPF arrows given the reactants and products

2. Draw the products given the reactants and EPF arrows.


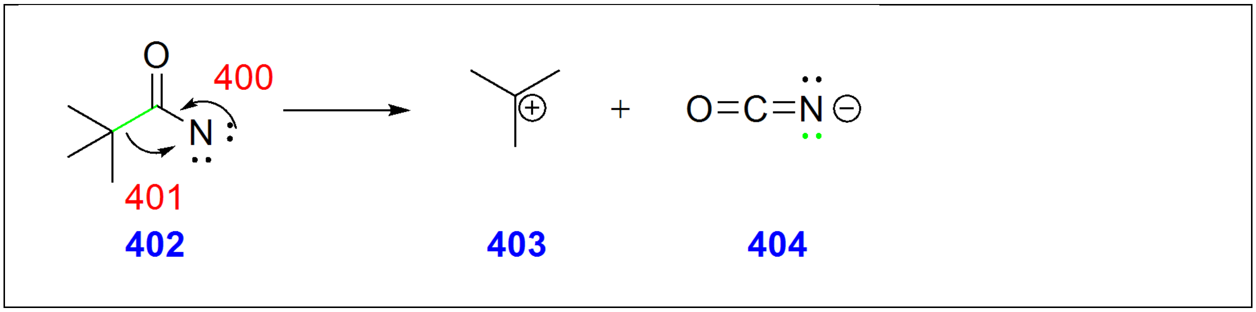
The researchers looked at 32 questions, 15 draw the arrow type questions, and 17 draw the product type questions, totalling 7411 questions analyzed. Of the number of questions, 3114 involved drawing the EPF arrows, and 4297 questions involved drawing the products. . The researchers found students scored higher on the drawing arrow type questions than on the product type questions. The average and median scores for the arrow type questions were 72% and 86%, respectively, while the average and median scores for the product type questions were 55% and 50%, respectively. Students performed better on questions that contained explicit atoms (atoms that are always explicit such as Cl for chlorine, median = 83%). Compared to implicit atoms that are not explicitly shown (carbon and hydrogen atoms, median = 50%). Students performed better on intermolecular reactions compared to intramolecular reactions (median = 75% and 50% respectively). Two questions were the same reaction but presented as two conformations that revealed significantly higher scores when presented in a pseudo-reactive conformation than another conformation where molecular rotations were required to achieve the reactive conformation (median = 100 and 0 respectively). Students were taught to expand on their structures in the lectures by drawing in non-bonding electrons, bonds, atoms, redrawing structures, and mapping (Flynn *et al.*, 2016). Students who chose to expand on their structures correctly did so (>90%). Expanding on the structures has been associated with successful problem-solving strategies (Bodé and Flynn, 2016; Flynn and Featherstone, 2017). Although there was a high success rate when students expanded on their structures, only a few students demonstrated the strategies. The researchers found minimal errors such as reversed arrows or illogical EPF arrows suggesting the students tracked electrons throughout the reaction and do find the EPF arrows meaningful. However, the study is limited to what students put on their exams, and students' thoughts and interpretations could not be captured.

Section 1.8: Transplanting electrons

The Flynn research group reported an error called transplanting, where students picked up an electron pair and placed them onto another atom (Flynn and Featherstone, 2017). Table 2 illustrates an example of an expected and transplanted answer. The expected answer is a single neutral molecule, and the transplanted response contains two molecules with opposing charges. Transplanting electrons is impossible as the process destabilizes two atoms to a high degree. The atom giving the electron pair would have an unfilled orbital that is reactive and unlikely to form as the more stable compound, the expected answer, is likely to be made. The expected answer is stable because there are no charges, while the transplanted answer contains two molecules with charges making both molecules unstable. In addition to the charges, the expected product has all of its orbitals filled. One of the transplanted products does not have a full orbital, making it highly reactive and unlikely to form in this reaction (Table 2 molecule 403).

Table 2. Example of the expected answer and transplanted response. The researcher's labels in red indicate EPF arrows. The researcher's labels in blue indicate molecular species. The researcher's markings in green are for visualizing where the electrons have moved.

Expected Answer

Transplanted response



Previous work at the Flynn research group with exam analysis found more than 50% of students transplanted electrons (Flynn and Featherstone, 2017). The exam study was limited to what was on paper. Thus, students' thoughts and reasons were unobtainable from the exam study. The interview study followed the exam analysis limitations to examine how students interpret the EPF arrows in reactions that are new to the students (Galloway *et al.*, 2017). Students in the interview study discussed the electron-pushing formalism arrows as electron-movement in addition to bond-breaking and forming processes. The transplanting error demonstrates students found it challenging to keep the electrons on the originating atom, even with instructions in the course. When evaluating the OrgChem101 module, similar transplanting errors with an intramolecular ring formation were observed (Carle *et al.*, 2020). However, further research is needed to see why students are transplanting electrons.

The interview study followed the exam analysis to get explicit evidence on students' interpretations of the EPF arrows when solving unknown reactions (Galloway *et al.*, 2017). The interview study looked at how students use and interpret the EPF arrows as a representation when solving unfamiliar reactions. Participants in the interview study discussed the electron-pushing formalism arrows as electron-movement, with some students connecting bond-forming and breaking processes. Participants' discussions of electron movement were organized into four categories, revealing how students interpreted organic chemistry representations (Figure 1). The four categories are mapping, charges, stepwise, and chemistry reasoning. Instead of relying on memorized reactions, students discussed electron movement throughout the interview (Galloway *et al.*, 2017). The four categories demonstrated students were thinking about how to draw the EPF arrows instead of relying on surface features or cues.

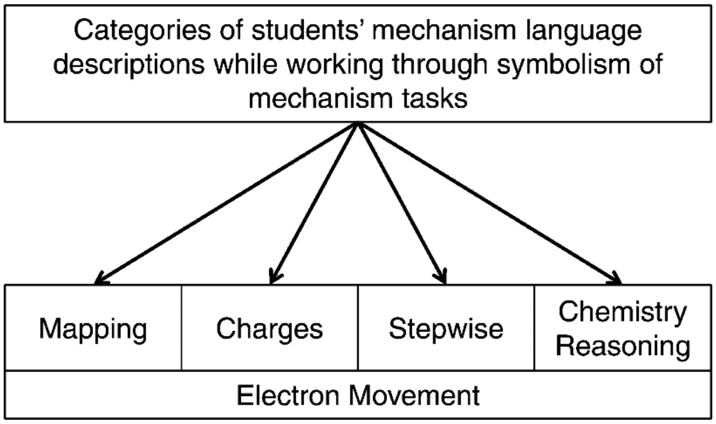


Figure 1. Categories of students' descriptions while working through the interview tasks. Image adapted from Galloway, Stoyanovich, and Flynn ***2017*** *with permission from the Royal Society of Chemistry.*

Section 1.9: Mapping strategy

Tracking atoms and electrons throughout a reaction is a strategy called mapping and has been associated with higher success rates when solving organic chemistry reactions (Bodé and Flynn, 2016). The mapping strategy tracks atoms and electrons by assigning a symbol to the atoms and electrons throughout the reaction. Figure 2 illustrates the mapping process. When the mapping strategy is applied, it is easier to visualize what occurs in the reaction. Figure 2 shows the mapping of the reactant and the product using numerals to label the carbon atoms. The labels depict a bond-forming between carbons 3 and 8 (Figure 2 green bond circled in products), with a positive charge on carbon 2, which means in the reactants, the π-bond (π-electrons) form a bond with carbon 8. Thus an EPF arrow is drawn from the π-bond to carbon 8 (Figure 2 EPF arrow in red). Without the mapping strategy each carbon atom blends in with the other, making it challenging to determine the appropriate reactive site Figure 3.

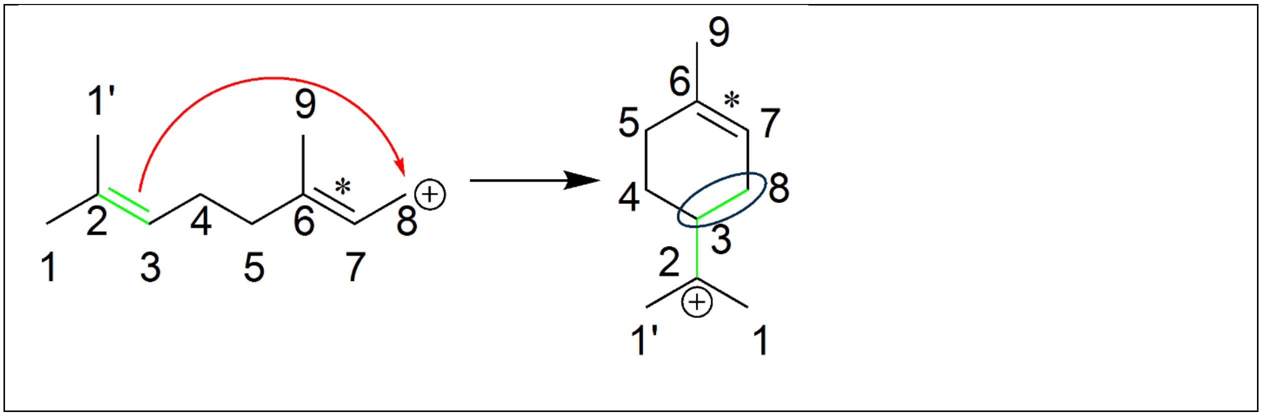


Figure 2. An example of the mapping strategy includes tracking atoms and electrons. The above image illustrates the atoms mapped with numerals and the pi bonds (electrons) using green bonds and an asterisk to differentiate the two.

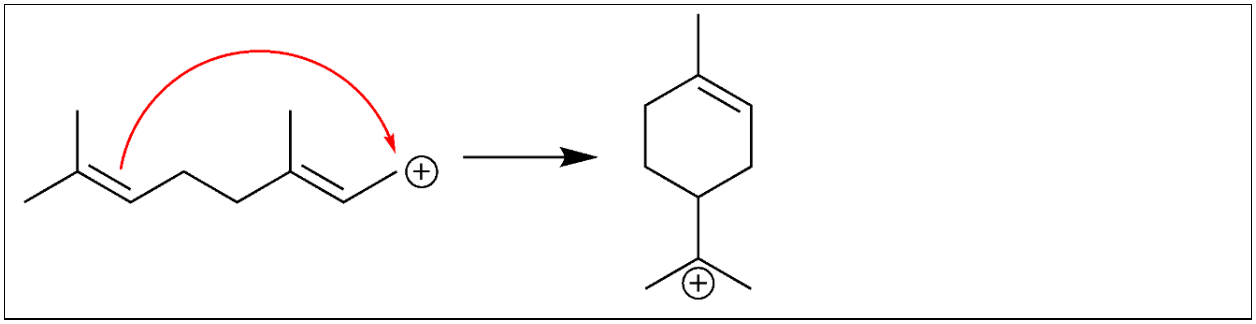


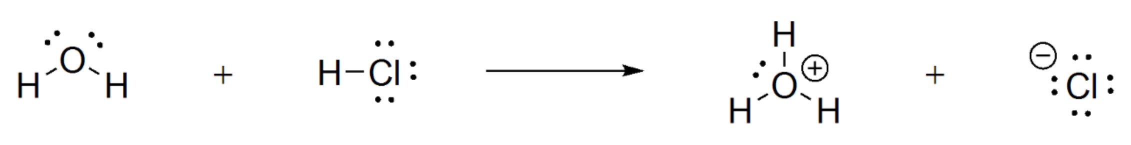
Figure 3 Example of no mapping strategy used.

Previous work at the Flynn Research Group (FRG) looked at students' mapping strategies. The exam analysis found minimal use of the mapping strategy, but when observed, the strategy was generally correctly applied (>90%) (Flynn and Featherstone, 2017). A limitation of the exam analysis is that students might have mentally mapped structures without physical labels and students' thought processes when applying the mapping strategy. Interview studies followed the exam analysis to probe students' understanding of mapping (Galloway *et al.*, 2017). The interview study found that students who mapped focused on several concepts, such as electron movement, demonstrated students' interpretations of the representations. Other students focused on comparing surface features such as charges or functional groups. The interview study was qualitative and should not be used to generalize. Another exam study looking at organic chemistry strategies found students who mapped were significantly more successful in synthesis questions than students who did not use the mapping strategy (Bodé and Flynn, 2016). The Flynn research group continued research on the effectiveness of the mapping strategy (Carle *et al.*, 2020). A pre-test and post-test of a learning module observed the mapping strategy's effectiveness. Students who mapped in the pre-test held a higher mean average score than those who did not. An intramolecular ring formation question displayed the most mapping and largest learning gains in the learning module, demonstrating the mapping strategy's advantages (Carle *et al.*, 2020). Feedback from students described a positive learning experience that would be beneficial when learning organic chemistry (Carle *et al.*, 2020). Further research is needed to see how students develop their mapping strategies.

Section 1.10: Charges as symbols

The international union of pure and applied chemistry (IUPAC) defines charged ions as atoms or molecules that gain or lose an electron, thus acquiring an electric charge (McNaught and Wilkinson, 1988). Table 3 shows the dissociation of hydrochloric acid in water. The oxygen atom loses an electron to become positively charged, and the chlorine atom gains an electron to become negatively charged. The interview study found that students gave explicit and implicit definitions of charged atoms when describing electron movement (Galloway *et al.*, 2017). Students accurately connected the EPF arrows that described an atom gaining or losing electrons with negative and positive charges, respectively, demonstrating an understanding of charges and the EPF arrows when interpreting reactions (Galloway *et al.*, 2017).

Table 3. The dissociation of hydrochloric acid in water. Emphasis on the number of electrons on the specific atom to determine the charge. A bond counts as one electron for this purpose.



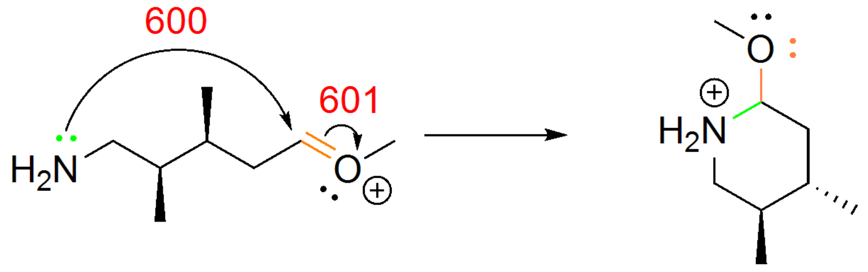
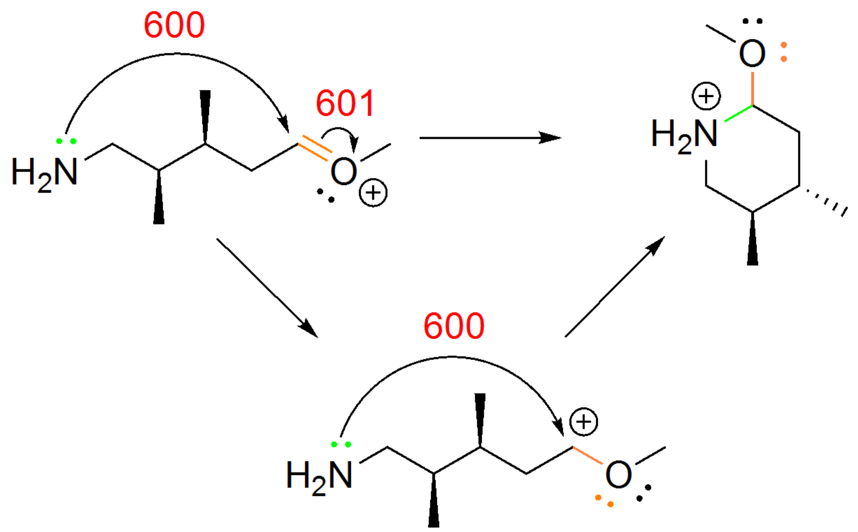
	Reactant	Product
Number of electrons on oxygen and the charge	6 — Neutral	5 — Positive charge
Number of electrons on chlorine and the charge	7 — Neutral	8 — Negative charge

Students in the interview study held several ideas regarding charges (Galloway *et al.*, 2017). Some of the language used by the students described charges as an object that moves, can be placed, or disappears, but it is unclear if students think charges are objects. Other students used charges to describe why a reaction occurs. Students' discussion of charges being reactive led to several ideas. Students correctly used charges to locate areas of reactivity and where bonds break or form, with some students heavily relying on charges to solve the questions. Similarly, a more experienced chemist may view the positive and negative charges as low and high electron density areas and interpret them as reactive sites. Students used charges in two ways while working through the interview tasks. 1) charges need to be neutralized, and 2) a positive and a negative charge are required to know how the step occurs. Students created additional charges to show a direct neutralization of charges. Further research is needed to see why students created the additional charges.

Section 1.11: Concerted and stepwise interpretations

The interview study found that students interpreted EPF arrows one at a time, reported as a stepwise interpretation (Galloway *et al.*, 2017). The stepwise interpretation is incorrect as the concerted interpretation of the EPF arrows occurring simultaneously is more accurate. For example, Table 4 illustrates a concerted interpretation where EPF arrows 601 and 602 occur simultaneously (correct). Table 4 also illustrates a stepwise interpretation, where EPF arrow 602 occurs first to create a minor resonance structure. Students used the minor resonance structures to help solve the reaction, but the minor resonance structure should not exist because both EPF arrows occur simultaneously. The minor resonance structures appear to be helpful to students, but further research is needed to fully explore why students created the extra resonance structure. Students justified their stepwise interpretation with the idea of electrons needing to be explicit and available to be used in the reaction. Some students described their stepwise interpretation as logical compared to the simultaneous interpretation of all the EPF arrows. The stepwise interpretation could be due to the amount of information processed at once while interpreting a singular EPF arrow one at a time to work through how reactants transition into products systematically. The research in this thesis will examine how students visualize the EPF arrows, stepwise or concerted, and if students use the stepwise interpretation as a problem-solving method.

Table 4. Example of concerted and stepwise interpretations.

Correct concerted interpretation **EPF arrows 601 and 602 occur as a simultaneous bond-forming and breaking process**

Incorrect stepwise interpretation **Interpreting the EPF arrows one at a time resulting in an unlikely intermediate structure**


Section 1.12: Theoretical Frameworks

A theoretical framework is a perspective that consists of concepts and definitions that are based on learning theories or empirical research. The primary purpose of a TF is to provide a basis for relevant literature, methods, and analysis (Grant and Osanloo, 2014). This thesis uses two frameworks, Johnstone's triangle and modern information processing theory. Johnstone's triangle is a perspective of learning in chemistry (Johnstone, 1991; Talanquer, 2011), and modern information processing theory is a cognitive perspective of knowledge building (Schunk, 2016).

Section 1.13: Theoretical Framework – Johnstone's Triangle, Chemistry Triplet

The chemistry triplet, Johnstone's triangle, describes how chemistry is communicated and learned across three distinct levels (Johnstone, 1991; Talanquer, 2011). The levels in Johnstone's triangle were originally named 1) descriptive and functional, 2) representational, and 3) explanatory (Taber, 2013), which have evolved to become the macroscopic, symbolic, and submicroscopic levels, respectively (Talanquer, 2011; Taber, 2013). The levels can be thought of as a triangle, with each level being unique and equally important, shown below in Figure 4 (Johnstone, 1993, 2009; Gilbert and Treagust, 2009; Talanquer, 2011). The macroscopic level describes the tangible phenomena observed. The submicroscopic level describes processes at the molecular level. Lastly, the symbolic level communicates the submicroscopic and macroscopic levels via representations. Johnstone argued that chemists build reality out of the three levels and reside at the center of the triangle. At the same time, novices operate at the macro level and find difficulty relating to other levels (Johnstone, 2009).

Talanquer 2011 and Taber 2013 described different perspectives of the chemistry triplet (Talanquer, 2011; Taber, 2013). Talanquer's perspective of the chemistry triplet was instructions focused on either the symbolic or the submicroscopic levels without instructions on bridging all levels (Talanquer, 2011). Alternatively, Taber's perspective of the chemistry triplet was that the symbolic level is not a level but a bridge that connects the submicroscopic and macroscopic levels (Taber, 2013).

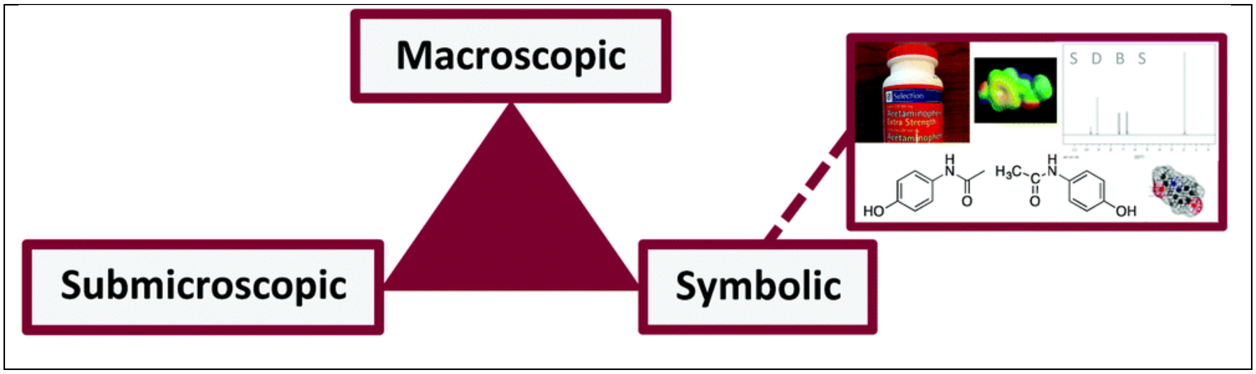


Figure 4. Johnstone's Triangle, the chemistry triplet. Image adapted from Galloway, Stoyanovich, and Flynn ***2017*** *with permission from the Royal Society of Chemistry.*

This thesis looks at what interpretation students have of the electron-pushing formalism arrows as symbols with respect to their submicroscopic processes. This work does not include the macroscopic level as no data were collected on students' perceptions at this level.

Section 1.14: Theoretical Framework – Modern Information Processing Theory

Information processing theory (IPT) views learning as acquiring information from a cognitive point of view (Mayer, 2012), illustrated in Figure 5. Stimulus enters through the sensory inputs that can be transferred to the working memory if deemed useful or lost if not. Learners use their working memory to oversee and process new and prior information. When information enters the working memory, learners can retrieve relevant prior knowledge from their long-term memory and connect the new and prior information (Schunk, 2016). When learners explicitly connect the new and prior information, the new information encodes with the prior information into the long-term memory for future use. Schunk compared IPT to a computational learning system where information is stored in a location and retrieved as necessary (Schunk, 2016).

Modern IPT differs from IPT because the viewpoint is of humans constructing knowledge by taking environmental, physical, mental, and emotional factors into account. (Schunk, 2016). Modern IPT differs from IPT as the sensory inputs include the environment (vision, hearing, touch, smell, and taste), time as factors when the learner perceives the information, how the learner feels at the time when receiving stimulus (mental and emotional), and what thoughts learners have when receiving information (contextual) (Schunk, 2016). Each sensory input registers information that the previous IPT framework did not cover, as the previous viewpoint on IPT was viewed in a computational manner. Ausubel's theory of meaningful learning supports IPT by defining how connections between new and old information are made (Ausubel, 1968; Bretz, 2001). First, the new information must be meaningful on its own. Second, the new information must present itself in a meaningful way. Third, the learner must have relevant prior knowledge to connect the new information. Lastly, learners make meaningful connections when they actively make the connections between new and prior information (Ausubel, 1968; Bretz, 2001).

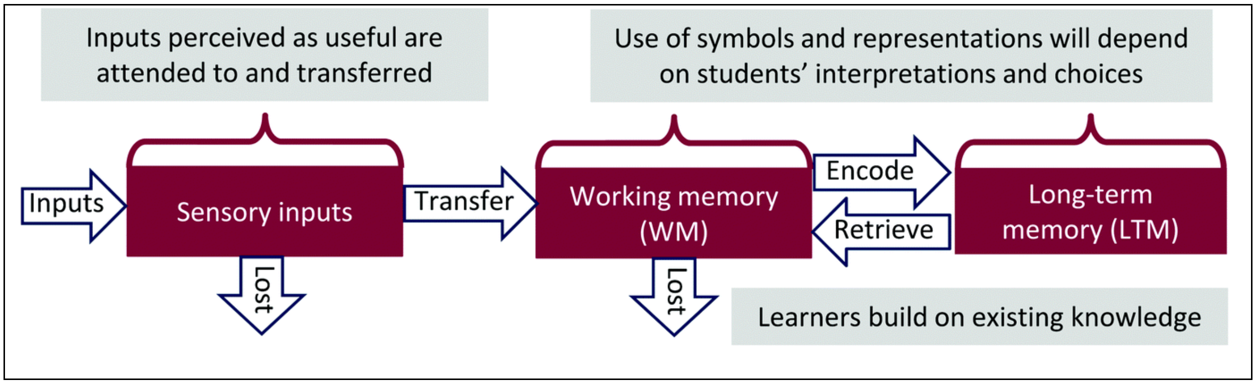


*Figure 5. Modern information processing theory. Image adapted from Galloway, Stoyanovich, and Flynn **2017** with permission from the Royal Society of Chemistry.*

The present study attempts to understand students' understanding regarding the EPF. While students work through the interview tasks, they will retrieve relevant information from their long-term memory via their working memory. This study explores students' relevant information about the EPF via discussions and drawings.

Section 1.15: Research Questions

The goal of this thesis research was to gain an understanding of how students initially interpret the electron-pushing formalism arrows to improve teaching and learning. The following research questions guide this work.

1. What meaning do organic chemistry students attribute to the electron-pushing formalism?
2. How do organic chemistry students visualize elements of reaction mechanisms, specifically: electron movement, concerted and stepwise interpretations, transplanting electrons, mapping, and charges?

Chapter 2: Methodology

Section 2.1: Participants

The Flynn Research Group recruited students enrolled in Organic Chemistry 1 (CHM 1321) via email in the Winter 2017 semester. All participants were volunteers and had taken Principles of Chemistry (CHM 1301 or 1311) in the Fall 2016 semester prior. Thirteen students consented to participate in this study. Eleven participants were in their first year and two in their second year. Nine participants were in a science-related program, one participant was in engineering, and the last three were in health sciences. All participants' names were changed to pseudonyms by Dr. Kelli Galloway.

After learning about the EPF arrows, participants were interviewed between February 13th, 2017, to March 7th, 2017. The course syllabus from Winter 2017 was obtained to determine what content was introduced (Appendix 1). The Winter 2017 course syllabus did not contain specific dates when topics were taught, while the Winter 2019 calendar had approximate dates of when content was introduced (Appendix 1). Using the Winter 2019 calendar for dates, the starting participants would have had a week of experience with the EPF arrows. The dates are important because participants have only just learned about the EPF, and any interpretation of the EPF arrows would be from the perspective of a new learner. The new learner perspective is important because the interpretations may be a common thought process. Determining where incorrect perspectives come from can be used to mitigate misconceptions and improve teaching and learning in organic chemistry. Students were taught the EPF in the first week of February to gain mastery of the curved arrows before adding in complex chemical concepts (Flynn and Ogilvie, 2015). Since participants were interviewed on or after the second week of February, it can be inferred that all participants would have been taught the EPF if they attended class.

Section 2.2: Ethics

The Research Ethics Board (REB) at the University of Ottawa granted the Flynn Research Group approval to conduct the investigations described in this work (REB File #H11-14-09). Participants signed consent forms for the Language of Mechanisms project that contained information regarding study funding, the purpose of the study, risks, benefits, confidentiality, anonymity, conservation of data, compensation of a $10 Starbucks or Tim Horton's gift card (participants who withdrew from the study still received compensation), voluntary participation, and consent to participate.

Section 2.3: Instrument and response process

The purpose of an instrument is to measure and obtain evidence of phenomena. In some research, such as qualitative interviews, an instrument may not measure what is intended and is thus invalid. Validity is the measure of evidence and theory supported by data (American Educational Research Association *et al.*, 2014). Collecting validity evidence is important to verify the instrument measured what it was supposed to (American Educational Research Association *et al.*, 2014). There are several types of validity evidence such as instrument content, response process, internal structure, relations to other variables, and consequential (American Educational Research Association *et al.*, 2014; Deng *et al.*, 2021). The research in this thesis focuses on cognitive interviews via response process and instrument content validity. Cognitive interviews provide a diverse perspective and sampling a population would be needed to validate the responses. Graduate students in the field can help pilot test the instrument for ambiguity or misinterpretations as response process validity. Graduate students have adequate knowledge in the subject and are a good representation of the intended population being researched, as they are going through the transition of student to professional. Experts can review the instrument and student responses to determine what is measure being measured as instrument content validity. Researchers can then identify any issues to improve subsequent interviews, how to evaluate responses, explicit instructions, and adjustments to the instrument (Deng *et al.*, 2021).

The instrument used in this work consisted of six organic chemistry reactions to elicit students' interpretations of the electron-pushing formalism (EPF). The nature of this work is qualitative, and thus the instrument measured participants' interpretations of the EPF arrow symbolism through discussions and drawings. The selected reactions elicited students' interpretations of the EPF arrows, which allowed us to look further and compare interpretations between studies (Flynn & Featherstone, 2017; Galloway et al., 2017). We used specific reactions that participants would not encounter in the courses they had taken to date, meaning participants would not have any pre-existing knowledge of the reactions and would have to interpret the representations. Table 5 summarizes the reactions, tasks, and associated learning outcomes. For example, Question 2 of the instrument was a Michael addition that Organic Chemistry 1 does not cover (Figure 6). We used specific reactions that were new to the participants, and each task had the objective of interpreting or applying EPF arrow knowledge. Dr. Kelli Galloway led the instrument development (Appendix 2).

Table 5. Types of reactions asked in the interview and associated learning outcomes.

Question	Reaction Type	Task	Associated Learning Outcome
1.	Acid-catalyzed acetal formation	Explain the mechanism	Explain the reaction given a complete mechanism, including starting materials, intermediates, products, and electron-pushing arrows.
2.	Michael addition	Draw the EPF arrows	Draw the electron-pushing arrows given the reactants, intermediates, and products
3.	Intramolecular carbocation ring formation		
4.	Curtius rearrangement	Draw the products of the EPF arrows	Draw the products given the reactants and curved arrows.
5.	Substitution reaction (S_N2)		
6.	Acid-catalyzed intramolecular ring formation		

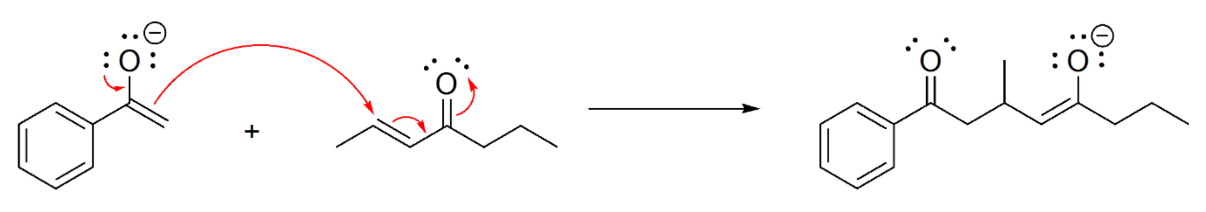


Figure 6. Question 2 Michael addition. The correct EPF arrows are in red.

Investigating response processes allows researchers to understand how responses are created (Deng *et al.*, 2021). The purpose of response process interviews, cognitive interviews, is to obtain an understanding of how respondents think and respond to prompts, emphasizing barriers or pitfalls that arise. Tourangaeu's four-stage cognitive model can provide insight into response processes (Groves *et al.*, 2010). The four-stage model describes respondents must be able to comprehend the task, retrieve relevant information to the task, use the relevant information to make judgements, and provide a response with respect to the task. Evidence of a response process would indicate that the respondent understood the task and provided their response to fulfill the task. There is also evidence against response process validity from the four-stage model that can give errors. The first stage assumes respondents understood the task when respondents might have misinterpreted the objective. The second stage assumes respondents pulled relevant knowledge when respondents might not have the appropriate information or had other memory issues. The third stage assumes respondents are accurate in their judgements when they might have flawed judgement or estimations. The fourth stage assumes respondents responded in a particular manner when problems such as formatting, misinterpreting, or following instructions can occur. A pilot study with graduate students can help reduce misconceptions or ambiguity with the tasks and provide evidence of response processes. Experts can review the graduate students' responses to adjust the instrument as needed.

Figure 7. Tourangaeu's four-stage model for response processes I recreated using PowerPoint (Groves et al., 2010).

Section 2.4: Interview Process

Dr. Kelli Galloway led the interview guide design, organized the interview structure, kept discussions relevant, and elicited student interpretations. The interview guide is essentially an overview of the interview to ensure each interview runs smoothly. The interview guide includes a checklist of steps to ensure each interview followed the same procedure, follow-up questions for probing further, specific follow-up questions, and things to avoid saying.

A think-aloud protocol was adopted and is commonly used in education research to elicit participants' thought processes (Bowen, 1994). A Livescribe pen, which captured participants' written and speech simultaneously, was used to record participants' thoughts and drawings as they interpreted and solved organic chemistry reactions. Interviews recorded used a Livescribe pen, which captures what you write and speak simultaneously, to record participants' thoughts and drawings as they interpret and solve organic chemistry reactions. The interviewer instructed participants to verbalize their thoughts as they answered each question to observe how students think and solve questions rather than getting correct answers. The interviewer reminded the participants we would still like to know what they thought even if it seemed irrelevant. Instructions at the start of each question. General statements and questions were prepared in the protocol to probe participants' thinking without cueing the participants to something specific (Table 6). The guide included things to avoid saying or asking to prevent leading the participant through any indications of affirmation or refutation, thus maintaining neutrality and resulting in an unbiased response (Table 6). Specific statements were used to probe participants further when previous findings arose, for example, transplanting electrons and stepwise interpretations (Table 7) (Flynn and Featherstone, 2017; Galloway *et al.*, 2017). Participants' incorrect interpretations were not corrected. The interviewer asked for clarifications about participants' interpretations, to understand their thinking as fully as possible. When participants were clarifying, the interviewer allowed them to speak regarding the topic until they had nothing left to say, resulting in a more complete response. Each interview lasted for approximately 1 hour. At the end of the interview, the interviewer asked participants if they would like to share anything and thanked them for their time. For more details regarding the interview guide and protocol, see Appendix 3.

Table 6. Example probing questions in the interview guide.

General probing questions
"What do you mean by that?"
"Please tell me more about that."
Things to avoid saying
Avoid affirmative language like "perfect," "great," or "awesome"
Avoid using functional group names or other chemical terminology before student

Table 7. Examples of the associated learning outcome for specific probing questions.

Specific probing questions	**Associated concept**
"How do you know the electrons go there?"	Curved arrows depict electron-movement and/or transplanting electrons
"What tells you the electrons go there?"	Curved arrows depict electron-movement and/or transplanting electrons
"How do you know that is the bond that breaks?"	Curved arrows depict bond-breaking processes
"How do you know that is the bond that forms?"	Curved arrows depict bond-forming processes
"What are you thinking about as you number the atoms?"	Mapping strategies (problem-solving)
"Are you thinking about the order of the arrows?"	Stepwise or concerted interpretation

Section 2.5: Analysis

Several group members and I transcribed the interviews verbatim, and then I performed a qualitative analysis to categorize participant interpretations. I removed filler words in the example transcripts, such as "Um," to reduce cognitive effort and maintain fluidity when reading. The appendices contain the full transcripts, demonstrating that I did not pick and choose text as a researcher but reported everything. I started by open coding participants' discussions in the transcripts. Open coding categorizes data (Creswell et al., 2014), where I categorized participants' discussions through similar concepts in the analysis. I used the perspective of the EPF (EPF) to help guide data categorization. I found participants' discussions of electron movement or the EPF arrows, looked further for specific ideas, and categorized them under the defined code (example in Table 8). I coded each unique discussion of EPF arrows, stepwise and concerted interpretations, transplanting electrons, mapping, and charges, with some discussions counting for multiple codes (Table 9).

Table 8. Example singular codes in participant discussion.

Code	Definition	Example
Curved arrows	Curved arrows depict electron movement (not atom movement)	#02: “*Well I interpreted like movement of electrons in particular from the arrows”*

Table 9. Example multiple codes in participant discussion. The researcher’s labels in red correspond to EPF arrows.

Code	Definition	Example and image
Curved arrows	Curved arrows depict electron movement (not atom movement)	 ***#01:** “There’s an **arrow*** [Arrow 1] ***from the bond um the bond to the oxygen atom** which means that this bond [Oxygen-Hydrogen] is going to be broken and **the electrons are going to go to the oxygen**.”*
Start and stop point of the curved arrows	Discusses how the arrow starts at an electron pair or bond and ends at an atom/bond	 ***#01:** “There’s an* **arrow** [Arrow 1] ***from the bond um the bond to the oxygen atom which means that this bond [Oxygen-Hydrogen] is going to be broken** and the electrons are going to go to the oxygen.”*

The first round of coding resulted in general codes used to organize and categorize, which helped guide the later rounds of coding. I looked at Questions 2 and 3 for a second analysis, specifically looking for any illogical or reversed arrows drawn by participants, as the other questions did not ask participants to draw EPF arrows. I reviewed the data a third time, looking for a specific idea in the transcripts, stepwise versus concerted interpretations of the EPF arrows. I reviewed the data for a fourth time, looking for any missing confirming or disconfirming evidence to ensure I reported all data without bias and to provide researcher credibility (Creswell and Miller, 2000). After coding all the transcripts, I created a codebook to summate all the codes (Appendix 4). I reviewed each transcript again using the codebook as a reference, comparing codes’ similarities and revising the codebook (Patton, 2015). I created a spreadsheet in Microsoft Excel to organize each unique code linked to the question number and the participant. I transferred the spreadsheets to open software, Miro-boards, to display all of the data on one screen to uncover any patterns in the discussion, as viewing all the data was a limitation with Microsoft Excel. The drawing files for Question 1 were missing for Participants #11 and #13, thus not included in this work. Participant #10's data files regarding drawings were corrupt, and I could not analyze or correlate any discussion with the participants' drawings. Thus, participant #10's data files were omitted from this analysis, making the total sample size twelve and two missing questions.

I performed two statistical tests to measure the reproducibility of findings when using the codebook as a guide. The first statistical test is the interrater review, which measures the percent agreement between two raters (McHugh, 2012). The percent agreement measures how likely both raters coded the same data. The second statistical test is Krippendorff's α, which measures how likely both data collectors coded the same data, verbal or written, by considering observed disagreement and expected disagreement (Krippendorff, 2004). I measured the reliability of the codebook by tasking a second-rater not involved in the project to code a subset of the data using the codebook as a guide, the process shown in Figure 8. I compared the discussions captured by the secondary rater and myself for any disagreements. After comparing discussions, the raters came to a consensus on any disagreements. I refined the codes and the codebook with respect to the consensus. I performed three interrater rounds that did not meet the required agreement and refined the codebook each time. The fourth and final interrater round completed used seven questions, ~10% of the data, chosen at random through a random unmber generator. The final percent agreement was 83% which is above the considered acceptable agreement of 80% (McHugh, 2012). The final Krippendorff's alpha of 0.95 is above the considered agreement of 0.80 (Krippendorff, 2004).

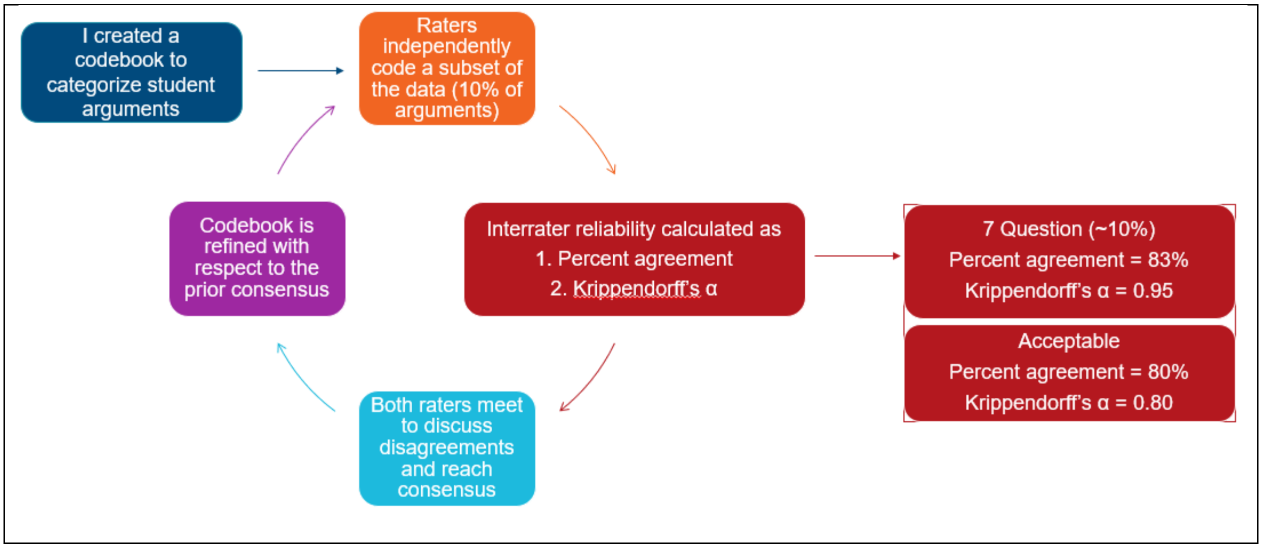


Figure 8. The interrater reliability process for the Language of Mechanisms codebook using percent agreement and Krippendorff's α.

Section 2.6: Limitations

The limitations of this work are qualitative, the think-aloud protocol for interviews, and the open-ended questions allowing participants to share their interpretations freely. The main limitation of this work is the qualitative nature meaning that all of the findings are specific to the participants in this study (Patton, 2015). Although the results can not be generalized, the findings provide insight into how students might initially interpret the EPF arrows, an essential part of Organic Chemistry. Thus, our goal is to find initial interpretations of the EPF arrows such that we can improve teaching and learning by addressing any issues as early as possible.

Previously identified limitations with think-aloud interviews are participants may find it unnatural to think aloud, the burden is placed on the participant to respond, and participants direct the conversation (Willis, 1994). The benefits of think-aloud interviews are that researchers can probe further whenever a topic of interest arises.

The interview contained six open-ended questions allowing participants to share their interpretations of the electron-pushing formalism freely. Some discussions were easily understood and categorized, while others were more difficult. Unfortunately, in 2020 Adobe stopped its support with the Livescribe pen, and the files were no longer playable as videos. I could not coordinate some audio and video as the files were unplayable, making some discussions challenging to analyze. I used only explicit data to reduce assumptions. The codebook was also created to reduce assumptions and to ensure the data was interpreted in the same manner. Several iterations of the codebook were used to improve the codebook to have an accurate direct interpretation of participant responses while avoiding assumptions. I reported what I could directly interpret regarding the difficult discussions while avoiding assumptions.

Chapter 3: Results

Section 3.1: Electron-pushing formalism arrows and electron movement

Expert chemists use the EPF arrows as a representational tool to explain why a reaction will or will not occur and explain outcomes such as stereochemistry (Bhattacharyya and Bodner, 2005; Ferguson and Bodner, 2008; Bhattacharyya, 2013, 2014; Flynn and Ogilvie, 2015). Some novices appear to struggle at proposing and interpreting EPF arrows (Anderson and Bodner, 2008; Ferguson and Bodner, 2008; Bhattacharyya, 2013, 2014; Flynn and Ogilvie, 2015; Caspari, Weinrich, *et al.*, 2018). Our goal is to understand students' initial interpretations regarding the EPF so that we can mitigate common misconceptions and improve teaching and learning. In this section, I reviewed participants' interpretations of the EPF, how participants draw EPF arrows, and what strategies participants use to problem-solve.

Section 3.2: Electron-pushing formalism arrows as electron movement

All participants described their understanding of the EPF arrows depicting electron movement (Figure 9). The Organic Chemistry curriculum at the University of Ottawa dedicates the initial reactivity section of the course to learning the fundamentals of the EPF (Flynn and Ogilvie, 2015). All participants described the EPF arrows as electron movement while working on questions 1 and 4. Participants described their interpretation of the EPF arrows as electron movement with or without prompts (Table 10). Participants accessed their long-term memory and demonstrated the connection between EPF arrows with electron movement. Participants interpreted the EPF arrow symbols as electron movement being the submicroscopic process.

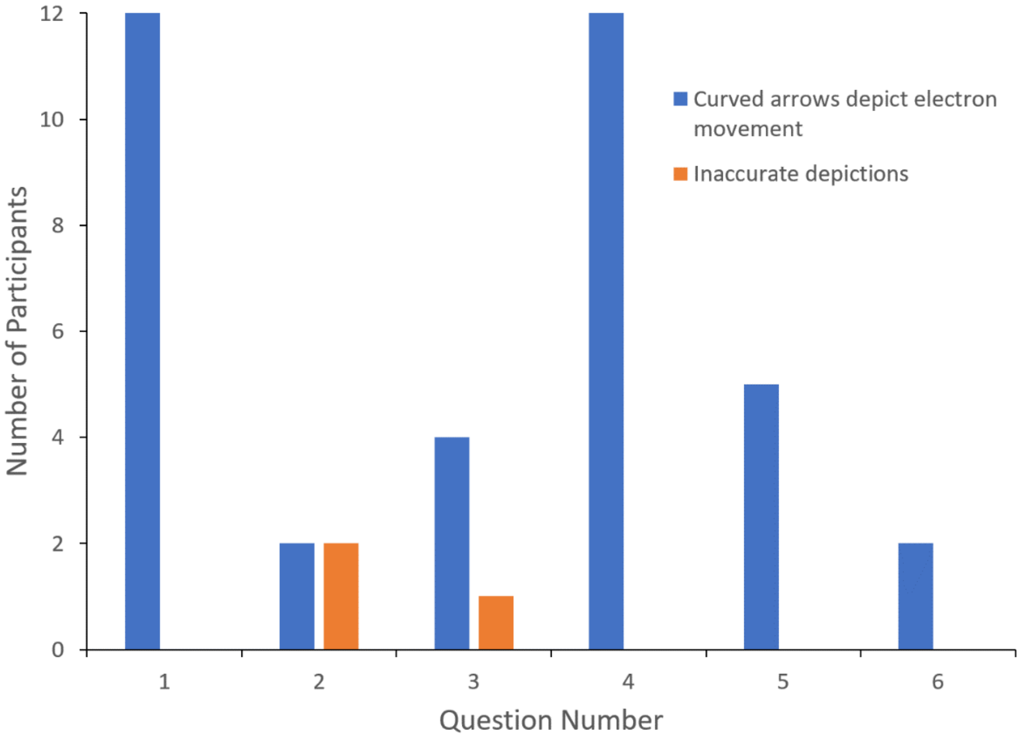


Figure 9. Frequency of when participants discussed electron movement with the EPF arrows. (N = 12).

Table 10. Examples of prompted and unprompted discussion of the electron-pushing formalism arrows as electron movement. Int is the interviewer. The numbers are the participant identification.

Prompted	
Int:	*"What do the curved arrows tell you?"*
#04:	*"where the electrons are going."*
#13:	*"the movement of electrons."*
Not Prompted	
#02:	*"I interpreted like the movement of electrons in particular from the arrows."*
#06:	*"That's what the arrows show, it's just moving electrons around."*

Section 3.3: Bond formation and breaking processes with respect to the EPF arrows

Forming and breaking bonds are critical aspects of organic chemistry. These processes are how molecules interact with each other. Every participant described bonds being formed or broken throughout the interview with respect to the EPF arrows (See Appendix 5 for all responses). For example, Participant #01 described a specific example where they interpreted EPF arrow 101 as an electron-pair from the oxygen pointing to the hydrogen atom, resulting in a bond, and EPF arrow 102 as the oxygen-hydrogen bond-breaking with the electrons moving onto the oxygen atom (Table 11). Some participants declared EPF arrows as either bond-forming or breaking without reason. For example, participant #07 declared EPF arrow 103 as bond-forming and EPF arrow 104 as bond-breaking (Table 12). Every participant described either an EPF arrow pointing from an electron pair to a bond as bond-forming or an EPF arrow pointing from a bond-to-atom as bond-breaking.

Table 11. Participant #01 explained their interpretation of EPF arrows 101 and 102. The researcher’s labels in red indicate EPF arrows.

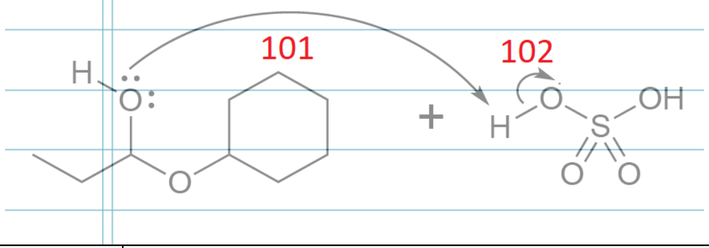
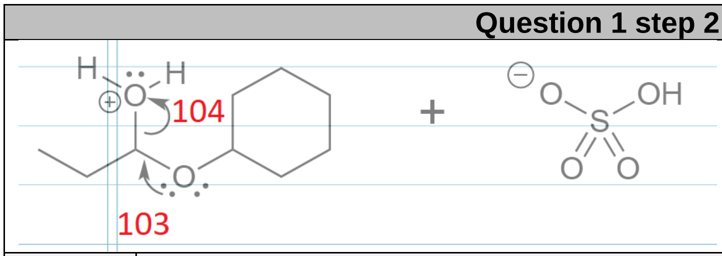
Question 1 Step 1 of 4	
	
#01:	*“**An electron pair from the oxygen is pointing towards the hydrogens** [Arrow 101] **so that must mean there’s a, there’s a bond that’s suppose to form between both of them** and **the bond is supposed to break from this hydrogen** [Arrow 102], between **this hydrogen and this oxygen** um **the electron is supposed to go to the oxygen**.”*

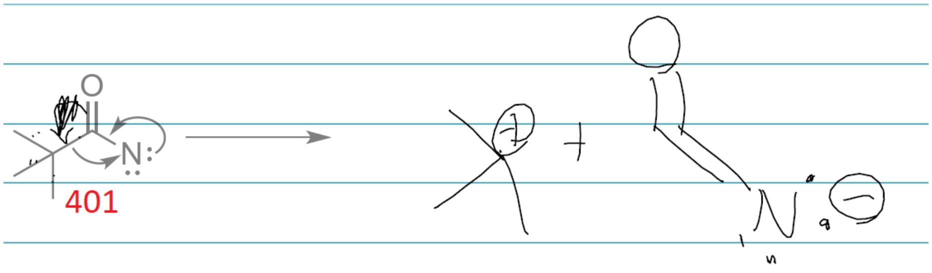
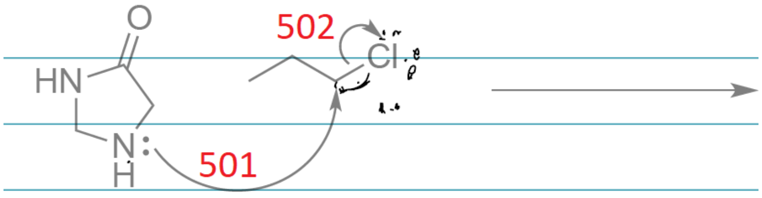
Table 12. Participant #07 referenced specific EPF arrows as either bond-breaking or forming. The researcher’s labels in red indicate EPF arrows.

Question 1 step 2 of 4	
	
#07:	*“**The bottom one** [Arrow 103] **shows that the electrons are creating a bond with the next—the carbon, the central carbon atom** and **then that’s [sic] carbon atom is, also breaking the bonds** [Arrow 104] so that re—releases water, releases water in the next — in the next step, I suppose.”*

Section 3.4: Generalized EPF arrow interpretation

Participants described the EPF arrows in the questions as either bond breaking or forming, with one participant providing a generalized interpretation of the EPF arrows. Participant #03 described a generalized interpretation of the EPF arrows as bond-breaking or forming. Participant #03 correctly described the bond breaks when the EPF arrow points from a bond-to-atom (Table 13 arrow 401), while working on question 4. Participant #03 correctly described a bond forms when an EPF arrow points from electrons to an atom (Table 13), while working on question 5. Participant #03 was the only participant to give a generalized interpretation of the EPF arrows.

Table 13. Participant #03 described their interpretation of specific EPF arrows as bond-breaking and forming. The participants' markings are in black. The researcher's labels in red indicate EPF arrows. The researcher's labels in blue indicate molecular species.

Question 4	
	
#03:	*“So this arrow* [Arrow 401] *shows to this bond is breaking because an arrow from a bond to an atom breaks the bond.”*
Question 5	
	
#03:	*“This arrow* [Arrow 502] *here shows that this bond is breaking. Because when something is pointing from a bond to an atom, the bond is breaking. So like things point* [Arrow 501] *from electrons to an atom, the bond is being formed.”*

Section 3.5: Accuracy of EPF arrow interpretations

I found minimal evidence of inaccurate depictions of the EPF arrow. Two participants described inaccurate depictions of the EPF arrows and attributed different factors. Participant, #01, described charges depicting electron movement where a charged species would either give or receive electrons (Table 14), essentially connecting charges to the movement of electrons. Participant #12 described EPF arrows depicting atom movement (Table 15).

Table 14. Participant #01 described charges depicting electron movement by giving or receiving electrons.

Attributing the movement of electrons to charges	
#01:	*“The **charges tell me the movement of the electrons**. For example if it has a charge, it needed an extra electron to be complete so it has more to share with and therefore more to move and sort of easier to determine um hmmm how many electrons that compound can give [...] to give or receive.”*

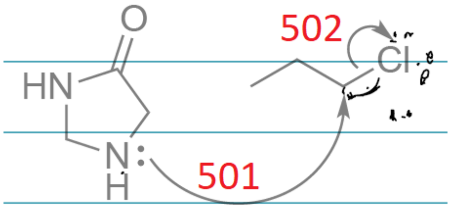
Table 15. Participant #12 described the EPF arrows depicting atom movement.

Question 2	
#12:	*"What happens is you have the movement of the carbon, um with the bond to this carbon."*
Int:	*"Okay, okay, so this arrow encompasses the movement of the carbon here."*
#12:	*"Yes."*
Question 3	
Int:	*"Okay. Could you show an arrow to show how that moves?"*
#12:	*"I guess like that, well (...drawing) more like, to show how the carbon's moving."*

Section 3.6: Summary

Every participant connected the EPF arrows to submicroscopic processes such as electron movement, bond-breaking and forming processes with minimal experience. Table 16 summarizes participants' interpretations of the EPF arrows. Participant #03 explicitly described how they interpreted EPF arrows as either bond-forming or breaking, while the other participants declared the same EPF arrows as either bond-forming or breaking. A similar conclusion regarding the EPF arrows and submicroscopic processes suggests all participants held the same interpretation of the EPF arrows, even if they did not explicitly state them.

Table 16. Participants' interpretation of EPF arrows as either bond-breaking or forming. The researcher's labels in red indicate EPF arrows.

Type of arrow	Image	Interpretation
Arrow 502 points from a bond-to-atom Arrow 501 points from an electron-pair to atom		Arrow 502 As bond-breaking Arrow 501 As bond-forming

Participants' prior knowledge most likely affected their responses as they were not given any instructions during the interview. Participants pulled relevant knowledge from their long-term memory to describe their interpretation of the EPF arrows. The lectures most likely played a role in participants' knowledge as two participants recalled being taught the EPF arrows. Participants could have also used the OrgChem101 module (Flynn *et al.*, 2016), which contains a submodule that focuses on teaching the EPF arrows and might have affected participants' knowledge. The participants recently learned about the EPF arrows and connected the EPF arrows as symbols to submicroscopic processes, demonstrating the participants' potential when learning and mastering the EPF arrows.

Section 3.7: Drawn EPF Arrows

Questions 2 and 3 of the interview tasked participants to draw the EPF arrows for a reaction, and I used the data from these two questions to answer RQ1. What meaning do organic chemistry students attribute to the electron-pushing formalism? Participants retrieved their knowledge on how to draw the EPF arrows, a chemistry symbolism, from their long-term memory and demonstrated the EPF arrow symbols are meaningful. I reviewed participants' drawn arrows, specifically reversed and illogical EPF arrows, and why participants drew their EPF arrows.

Section 3.8: Comparing surface features as an initial strategy

Every participant similarly approached questions 2 and 3 by comparing surface features of the reactants and products to determine how to draw the EPF arrows. For example, participant #01 emphasized looking at the product and the associated electrons to determine where a bond will form (Table 17). Participant #07 compared the charges between the reactants and products (Table 18). The other ten participants used similar strategies that compared molecules, bonds, atoms, and electrons as surface features (Appendix 6).

Table 17. Participant #01 compared the reactants and products in terms of bonds and electrons. The participants' markings are in black. The researcher's labels in red indicate EPF arrows. The researcher's labels in blue indicate molecular species.

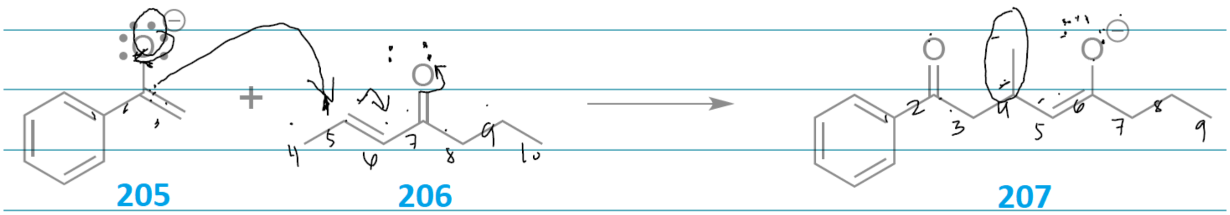
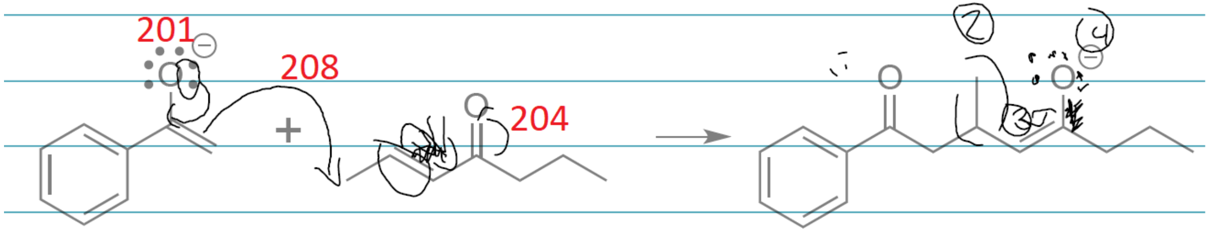
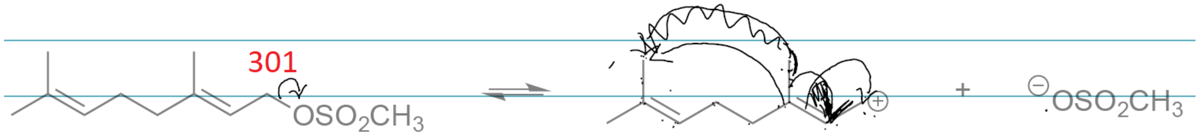
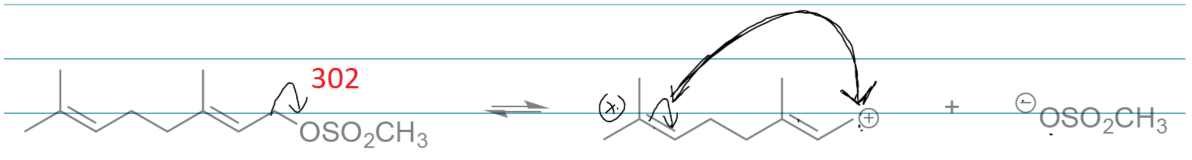
Question 2	
 **205** **206** **207**	
#01:	*"I'm looking at the product and I'm seeing where the bond is supposed to form […] And then I have to figure out which electrons move to make which bonds."*
Int:	*"Talk to me about why you decided to work through the problem in that way and how that helped you to be able to know where to draw the arrows."*
#01:	*"I think it was mainly because I was looking at the products [Molecule 207] so it was easier to know how the bonds were going to move um to form the compound […] I saw this how it looks like in the product then it has to make a connection the first one [molecule 205], the first one has to make a bond with the second one [molecule 206] through this carbon [molecule 206 carbon 5]."*

Table 18. Participant #07 compared the charges between reactants and products. The participants’ markings are in black.

Question 2	
	
#07:	*“I circled the electrons and moved it to the bond to crea—to remove the negative charge and make it a double bond with the oxygen.”*
Int:	*“Okay, why did you decide to do that.”*
#07:	***“Cause of the neg—in the products I see there’s a double bond made, no charge and the electrons are all gone.*** *”*

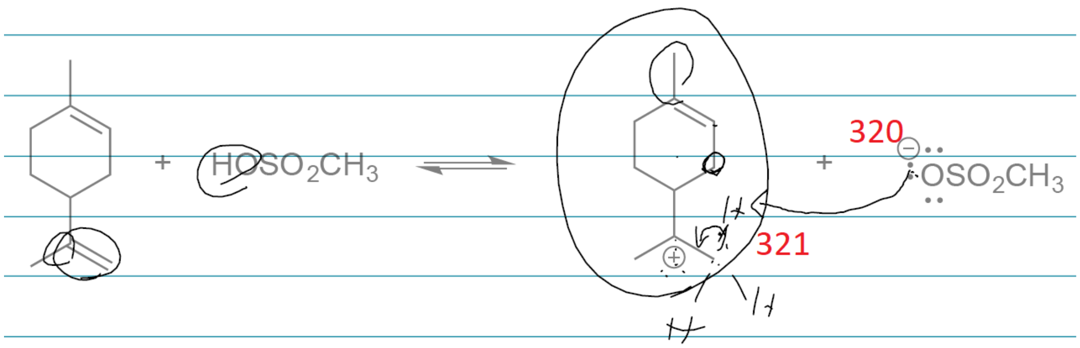
Similarly, every participant approached question 3 by comparing the number of molecules on the reactant and products. For example, six participants described two molecules as products, and the electrons from the carbon-oxygen bond moved towards the oxygen atom resulting in EPF arrow 301 (see Table 19 for examples). All participants’ responses with correct EPF arrow 301 are in Appendix 7. Four participants held the same interpretation that the reactant splits into two products (Table 19 and Appendix 8), but the drawn EPF arrow starts from the carbon atom and points to the oxygen atom.

Table 19. Participants compared the reactant and products for question 3, step 1 of 3. The participants’ markings are in black. The researcher’s labels in red indicate EPF arrows.

Question 3 step 1 of 3	
	
#12:	*“From the products in the first part, I see that the molecule is like now two parts. […] I know that like somewhere a bond has to break […] the first bond move on to the oxygen [arrow 301].”*
Question 3 step 1 of 3	
	
#04:	*“Because it becomes two molecules and it has the oxygen over here that means one of the bonds must’ve broken [...] the bond between the oxygen and the carbon is broken [arrow 302].”*

The participants who drew the correct EPF arrows for question 3, step 3 of 3, held similar reasons for drawing their EPF arrows. For example, participant #03 compared the charges between the reactants and products to determine that an alkene was created and where the alkene was created, resulting in the correct EPF arrows 320 and 321 (Table 20). Similarly, five other participants compared the charges on the reactants and products to determine that the carbon-hydrogen bond would break, resulting in the EPF arrows 320 and 321 (Appendix 9).

Table 20. Participant #03 compared charges between reactants and products. The participants’ markings are in black. The researcher’s labels in red indicate EPF arrows.

Question 3 Step 3 of 3 reading right to left	
	
#03:	*“**I’ve got that positive charge on the carbon.** […]. **I have to form this double bond here** [circled in black in the products] **right**. **So I have to figure out a way to take, to take a hydrogen from here**. […] **I’m going to break that bond and give it there**. **And have a double bond there, and take these to form the “O” and the “H” to give us this** [Arrow 320]. And then that double bond that was between the double bond and the “H” and **hydrogen would break to form a double bond here** [Arrow 321].”*

Section 3.9: Similar surface feature approach with differing EPF arrows

Although every participant approached question 2 by comparing surface features, the drawn EPF arrows differed. Participant #01 correctly drew the EPF arrow for question 2 (Table 17). However, seven participants drew the same incorrect EPF arrow (Table 21 arrow 208), drawn from the methylene to the methane carbon (Table 21 green circles on molecules 205 and 206, respectively). For example, participant #11 determined the bond location through labels and drew EPF arrow 208 (Table 21), or participant #07 compared the reactants and products and drew EPF arrow 208 (Table 22). Five other participants described a similar surface feature comparison and drew EPF arrow 208 (Appendix 10).

Table 21. Participant #11 described a connection on the 7th carbon atom on molecule 206, resulting in EPF arrow 208. The participants’ markings are in black. The researcher’s labels in red indicate EPF arrows. The researcher’s labels in

blue indicate molecular species. The researcher's circles in green are to label the methylene and methyl groups. The researcher circle in orange indicates the bond-forming location.

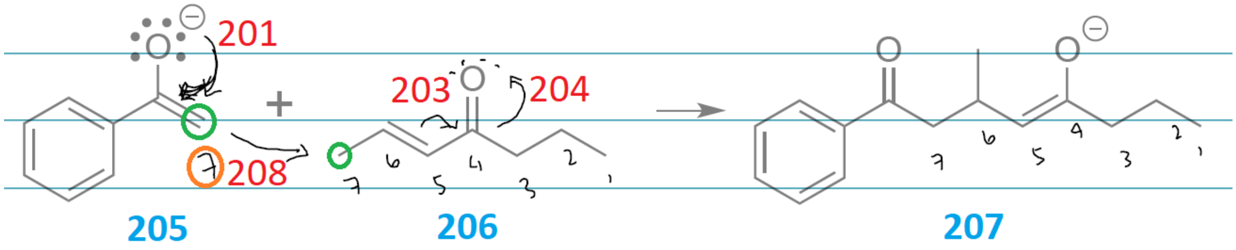
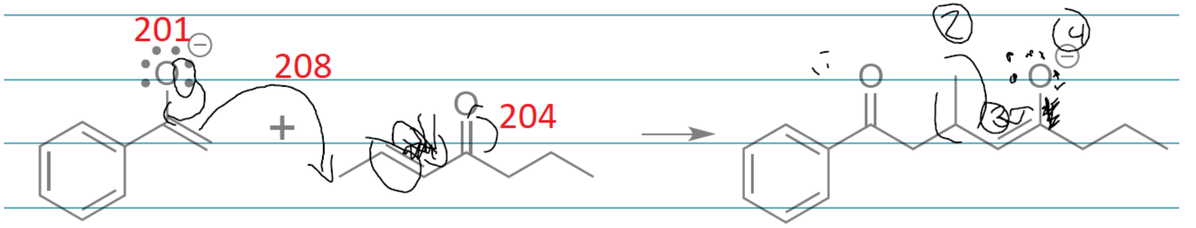
Question 2	
	
Int:	*"What does the labeling tell you?"*
#11:	*"Oh the carbons? […] Um, the position of the car…, into each individual carbon"*
Int:	*"What did you label that one right there?"*
#11:	*"Oh seven 'cause that's kind of where it connects right now."*
Int:	***"What about the other seven you have****? [circled in orange]"*
#11:	***"That's just saying this is where it connects."***

Table 22. Participant #07 compared the product and reactants to determine the EPF arrows. The participants' markings are in black. The researcher's labels in red indicate EPF arrows.

Question 2	
	
Int:	*"This arrow [arrow 208] is it point—pointing at that carbon there at the end or."*
#07:	*"Yeah, yeah."*
Int:	*"Thanks, um, tell me um, how did you identify uh, how to draw those arrows?"*
#07:	*"I looked at the product—product side […] to see what changed from the two original reactants and then processed going backwards."*

Section 3.10: Assessing participants' drawn EPF arrows

Two participants drew illogical EPF arrows that were unique, but their statements could not be aligned with their drawings, and thus only their drawings were analyzed. For example, participant #04 used words like "double bond," "single bond," and "two electrons" which could not be accurately analyzed as there were multiples of each term used in the transcripts. Participant #04 gave plausible EPF arrows (Table 23 arrows 201, 202, and 209), but EPF arrows 210 and 211 are illogical (Table 23). Participant #04 gave plausible EPF arrows (Table 23 arrows 201, 202, and 209), but the rest of the EPF arrows drawn are unclear as to what they represent. Similarly, participant #05 used similar vague language and provided two correct EPF arrows (Table 24 arrows 203 and 204). However, the rest of the EPF arrows drawn are unclear as to what they represent.

Table 23. Participant #04 drew plausible EPF arrows (201, 202, and 209), with the rest of the EPF arrows being unclear. The participants' markings are in black. The researcher's labels in red indicate EPF arrows.

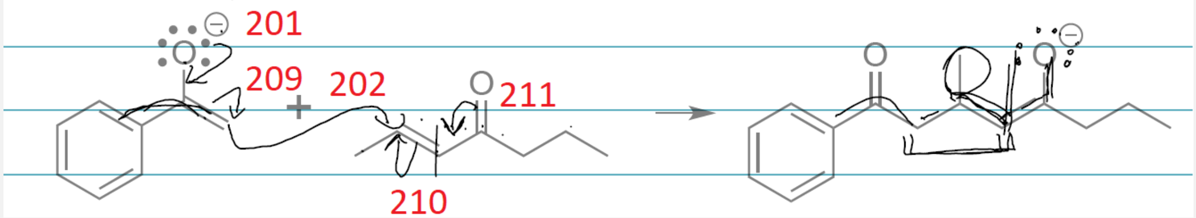
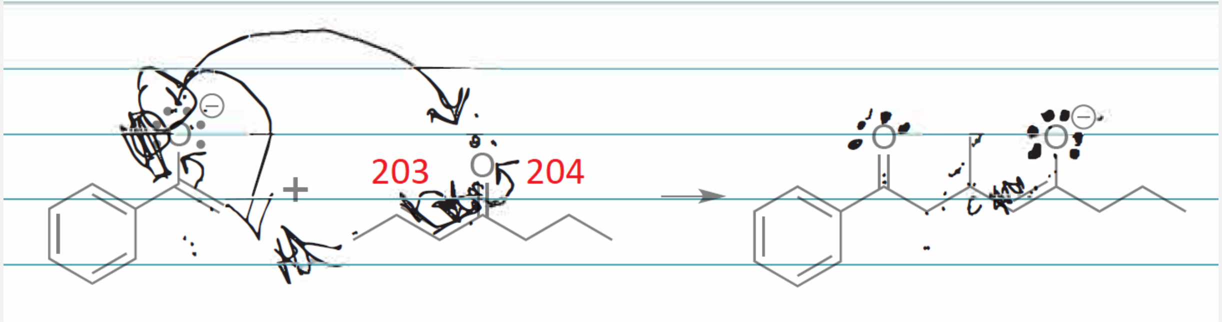
Question 2	
	
#04:	*"There would be this double bond but these two electrons have no charge, the carbon would have, but itself it would have two electrons and then uh, because it has a pi and it would only have two hydrogens attached to it, plus uh (...drawing) wait, one, two, three, four, five, six, seven, one, two, three, four, five, six, seven. Ugh this with the the double bond over her-oh uh single bond now and then this would be a double bond. Oh wait one, two, three, four that would have none, okay no that would be the same, okay so this one would be there but then this, wo- this one, where would that go, that would, that would create five bonds with this so then this is- one would probably go to this one instead, so this carbon would be left with two electrons, I think."*

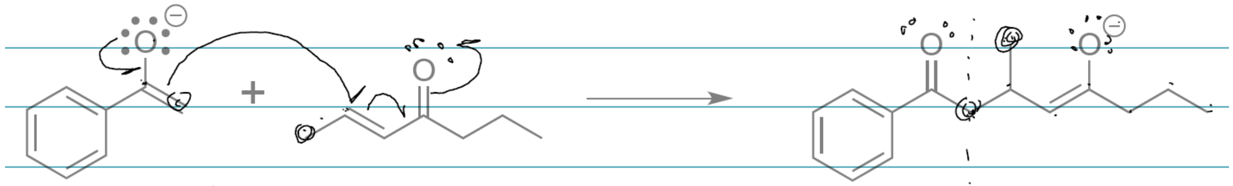
Table 24. Participant #05 drew correct EPF arrows 203 and 204, with the rest of the EPF arrows being unclear. The participants' markings are in black. The researcher's labels in red indicate EPF arrows.

Question 2	
	
#05:	*"I guess like one of these pairs of electrons um would come (...drawing) wait so this is like, easier if you like broke it up and put it like this one […] And then you want to put it together okay so I think may- oh so I think this pair of electrons here would make a double bond there […] And then um so this one here I guess, one double bond came here and then so this- one, two."*
Int:	*"What are you counting?"*
#05:	*"The b- the number of bonds so, okay so here there's one, two, three, four."*

Section 3.11: Singular-headed and double-headed EPF arrows

Participant #06 described not knowing the difference between singular and double-headed EPF arrows (Table 25). Participant #06 drew EPF arrows with a singular head versus the rest of the participants who drew double-headed EPF arrows. The number of arrowheads determines the number of electrons that move, where a single-headed arrow depicts a single electron moving, and a double-headed arrow depicts two electrons moving. Participant #06 described not knowing there was a difference between the two types of EPF arrows. Although participant #06 used singular-headed EPF arrows, they provided the correct direction and placement of the EPF arrows demonstrating participant #06 understood the purpose of the EPF arrows and held an incorrect idea on the number of arrowheads.

Table 25. Participant #06 describing not knowing the difference between a singular versus double-headed EPF arrow. The participants' markings are in black.

<table>
<tr><th colspan="2">Radical EPF arrows</th></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Int:</td><td><i>"For your arrows you have it, only on one side of the line instead of on both sides here."</i></td></tr>
<tr><td>#06:</td><td><i>"Well that's just […] 'cause I'm lazy […] Drawing arrows sometimes in my notes I do the one sided, sometimes I do the two sided […] Yeah tha- there's no real […] reason to that, it's just I don't know if there is a difference between them."</i></td></tr>
</table>

Section 3.12: No EPF arrows

Three participants did not provide any EPF arrows for question 3, step 2 of 3, for similar reasons where the participants got stuck. Participant #09 described losing a double bond between the reactants and products but did not draw an EPF arrow (Table 26). Similarly, participant #11 described losing a double bond and included a positive charge taking the double bond's place but did not draw an EPF arrow. Although participants #09 and #11 correctly described the changes that occurred in the reaction, they could not draw an EPF arrow. Lastly, participant #02 incorrectly decided that EPF arrows were unnecessary as the step was a conformational change and thus, did not draw any EPF arrows. Although some participants could correctly describe what is occurring in the reaction, they could not draw EPF arrows to represent their interpretation.

Table 26. Participant #09 compared the reactants and products with no EPF arrows drawn (top and bottom respectively). The participants’ markings are in black.

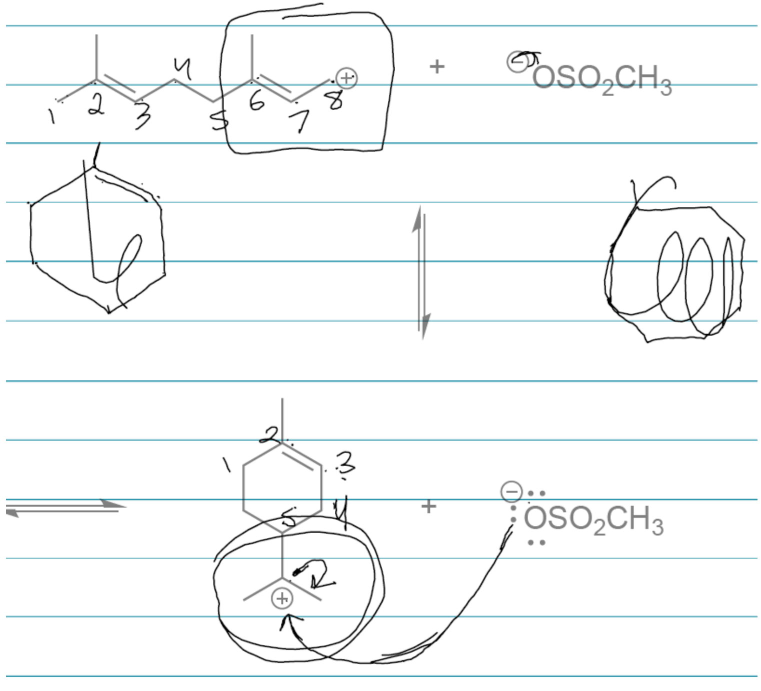
Question 3 step 2 of 3	
	
#09	***“I’m trying to figure out how the line diagram*** *[…]* ***Became um a cyclic structure****, there’s* ***that methyl group which is consistent, so […] somewhere here we lose a double bond*** *[…]* ***There isn’t a double bond here*** *[…] I don’t think that that arrangement can happen from that […] With these little methyl groups, I’m not sure […]* ***I’m not sure, um yeah this somehow, this all becomes this and then there’s an extra hydrogen left over*** *[…]* ***For that but I’m not sure*** *[…]* ***So (laughs) I’m gonna leave it there.”***

Table 27. Participant #11 compared the reactants and products with no EPF arrows drawn (top and bottom respectively). The participants' markings are in black.

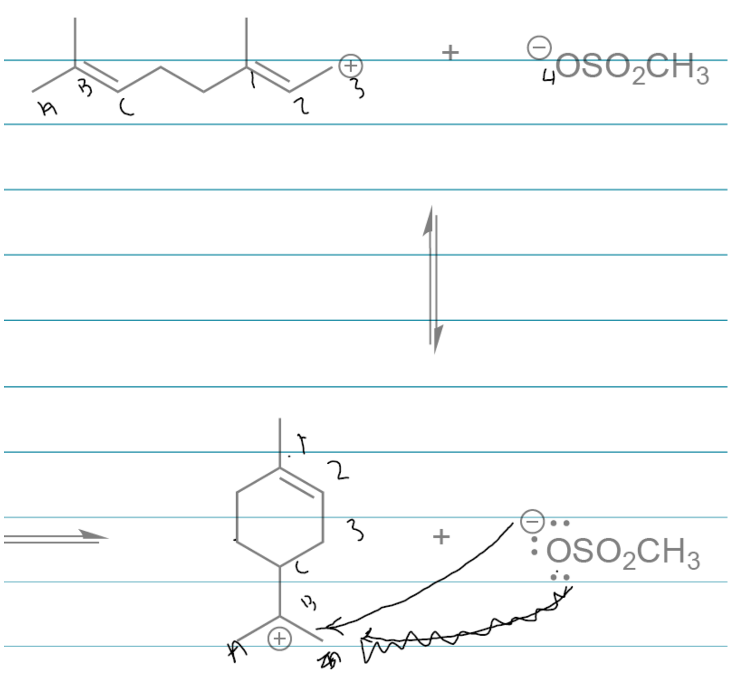
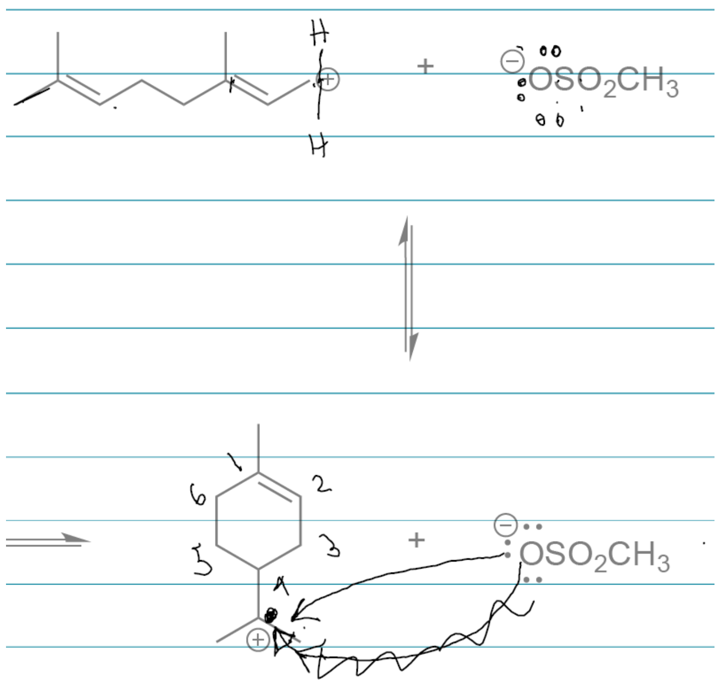
	
#11:	***"There is a double bond. But when you, it forms the cyclo part, the double bond is missing. And instead you have a positive charge****."*
Int:	*"Okay Okay. Um, could you tell me something about how you decided that those were the same carbons?"*
#11:	"**I labeled them one two so I'll just label them one two again** […] ***So my best guess would be the double bond at one two kind of stays there****, um, and for the positive on three and double bond from b,c a, not sure what happens to those two […]* ***I'm pretty much out of guess***."

Table 28. Participant #02 described EPF arrows were unnecessary for the conformational change. The participants' markings are in black.

	
#02:	*"I'm just trying to figure out how this shape is being made. […] I know I'm not gonna draw any arrows, because there's no transfer. It's just uh a shape change. Conformation change."*
Int:	*"Are you saying you're not sure that there's an arrow needed to form that ring?"*
#02:	*"Yeah, cause the arrows to me mean that the electron movement. And so I don't think there's an arrow needed."*

Section 3.13: Participants drew EPF arrows that started from an appropriate electron-source

Nine participants drew EPF arrows starting from an appropriate electron source. The nine participants drew their EPF arrows starting from an alkene while working on question 3, step 2 of 3. For example, participant #04 gave plausible EPF arrows by comparing the functional groups in the reactant and products and drew two plausible EPF arrows (Table 29 EPF arrows 311 and 312). The rest of the participants drew incorrect EPF arrows. Four out of the eight participants drew an EPF starting from the correct alkene but pointed to an incorrect position. For example, Participant #07 compared the product and reactant to determine that a double bond was lost and the ring formed, resulting in EPF arrow 313, which starts from the correct alkene but points to an incorrect position (Table 30). The four participants' responses regarding a drawn EPF arrow starting from the correct alkene but pointing to an incorrect position are in Appendix 11. Two participants drew multiple EPF arrows that started from one of the two alkenes, with each EPF arrow pointing to an incorrect position. For example, participant #07 drew two EPF arrows, 313 and 314, that started from one of the two alkenes but pointed to incorrect positions (Table 30). The last four participants similarly drew an EPF arrow starting from the incorrect alkene and pointed to an incorrect position (Appendix 12). For example, participant #06 compared the reactants and products to determine that one of the double bonds was missing in the cyclohexane structure and that sp3 carbon atoms do not have any electrons meaning they cannot bond, resulting in EPF arrow 315 (Table 31). All of the participants who attempted question 3, step 2 of 3, drew an EPF arrow from one of the two alkenes demonstrating participants were thinking about electrons as they drew their EPF arrows.

Table 29. Participant #04 drew plausible EPF arrows. The participants' markings are in black. The researcher's labels in red indicate EPF arrows.

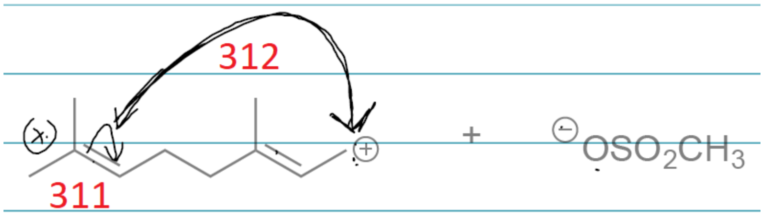
Question 3 step 2 of 3	
	
#04:	*"It created the cyclohexane, like the molec- this molecule itself created uh this cyclohexene […] the positive end is over here so, […] the double bonds must've broken in order to create the actual bond […] probably because of this formal charge that that cyclo- cyclohexane would uh, cyclohexene was probably created."*

Table 30. Participant #07 drew EPF arrow 313, which starts from the correct alkene but points to an incorrect position and EPF arrow 314 starts from the incorrect alkene and points to an incorrect position. The participants' markings are in black. The researcher's labels in red indicate EPF arrows.

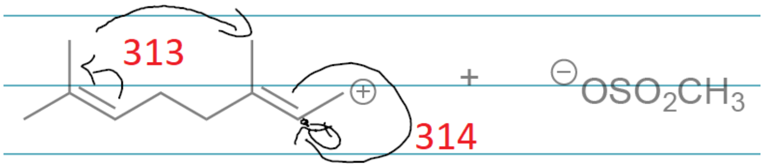
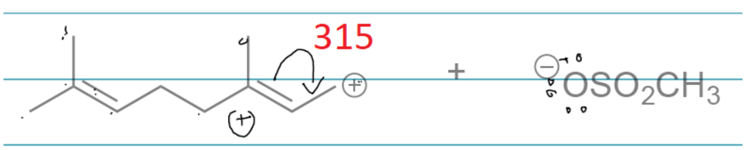
Question 3 step 2 of 3	
	
#07:	*"See if this double bon- which you connect this to close it off, this the double bond, is it at the same place as the bottom product. […] I saw this double bond here, I saw the products, I saw that there is only one double bond in the pro- this new prod- this third step here so and there is an extra si-side chain to the compound and so there is a double bond so somehow that double bond changes and moves around to form a product."*

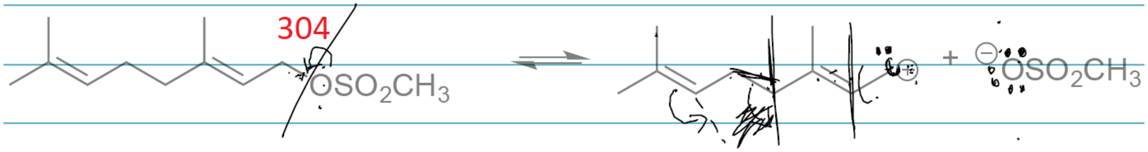
Table 31. Participant #06 drew EPF arrow 314 starting from the incorrect alkene that points to an incorrect position. The participants' markings are in black. The researcher's labels in red indicate EPF arrows.

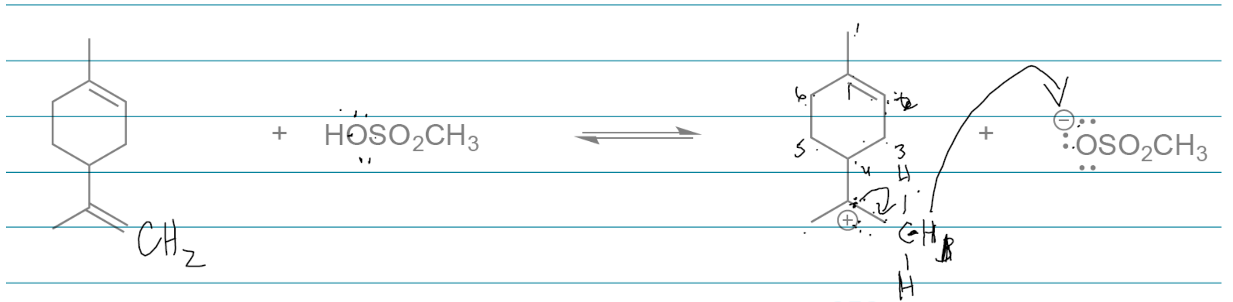
Question 3 step 2 of 3	
	
#06:	***"There's a double bond inside the um, inside the, the, the ring so I'm going to assume that that means one of these, either this or this […] Um, might not get touched*** *[...] So right now I'm trying to look for how, just how the ring forms really […]Also, this methyl group coming off of it, it's, just seems very convenient to have it that way […]* ***Well this has- this is sp3, it has all its hydrogens, it doesn't have any lone pairs coming off of it, um there's nothing, there's no real movement."***

Section 3.14: Reversed EPF arrows

I found minimal reversed EPF arrows for the first and third steps of question 3. Any reversed EPF arrow would be a misinterpretation and is important because it provides a new interpretation perspective. The reversed EPF arrows point in the opposite direction of the correct EPF arrow. For example, participant #05 drew a reversed EPF arrow and described not knowing how to draw appropriate EPF arrows while knowing the carbon-oxygen bond breaks (Table 32 EPF arrow 304). The EPF arrow is reversed as the EPF arrow should point from the carbon-oxygen bond to the oxygen atom. For the third step, three participants drew reversed EPF arrows. For example, participant #01 drew a positively charged carbon atom giving electrons. Participant #01 described the hydrogen moving towards the negative charge resulting in the drawn reversed EPF arrow (Table 32). Appendix 13 contains the other two participants' responses.

Table 32. Examples of reversed EPF arrows by participants #05 and #01. The participants' markings are in black. The researcher's labels in red indicate EPF arrows. The researcher's labels in blue indicate molecular species.

Question 3 step 1 of 3	
	
#05:	*"I see, yeah the reactants, and then I see it looks like it like, they broke it up into like the main molecule."*
Int:	*"Okay, okay so for this first step, is there an arrow that you could draw in to um show how that happens? [...] How do we- how do we form this from this?"*

#05:	***“Um you b- you break the bond between them****. […]So now they each have their electrons like showing, ‘cause they’re not bonded together through like lines or anything.”*
Int:	***“Okay, okay, what kind of curved arrow would you show to break the bond between them****?”*
#05:	***“I’m not sure*** *[...]* ***Yeah I’m not sure how you’d show it really*** (laughs), ***I’d put like a line like, it’s just broken.***”
Question 3 step 3 of 3	
 353	
#01:	*“Lets see how many electrons would this one have. Because there’s a positive charge [Molecule 353 carbocation]. It only has six […] this hydrogen goes to this charge over here. And that’s why there’s no charge on that side cause then you’d have that and you’d have to share these electrons.”*

Section 3.15: Illogical EPF arrows

I found minimal illogical EPF arrows for the first step of question 3, but multiple errors for the second and third steps (Section 3.2.6). Illogical EPF arrows are arrows that do not make sense. Like the previous strategies, participants compared the reactants and products to determine whether a bond would break, but the drawn EPF arrows were illogical. For example, participant #01 described the oxygen-carbon bond-breaking with the electrons moving to the carbon atom to give the carbon atom a charge, resulting in a correct EPF arrow to their interpretation but incorrect to the question (Table 33 arrow 303). I observed two incorrect EPF arrows drawn by participants on questions 3, step 3 of 3, summarized in Table 34. The incorrect EPF arrows correctly started from the oxygen atom but incorrectly pointed to either the carbon-carbon bond or the positively charged carbon atom. For example, participant #02 described not knowing how the double bond would be made and drew EPF arrow 323 (Table 34), starting from the oxygen atom and pointing to the carbon-carbon bond. Similarly, participant #05 described using the oxygen atom to create the double bond and drew the EPF arrow 324 directly to the positive charge (Table 34). Alternatively, participant #08 drew too many illogical EPF arrows that were too cluttered to decipher, and their discussion could not be correlated to the drawings (Table 35). All examples for illogical EPF arrows on question 3, step 3 of 3, are in Appendix 14. Although the EPF arrows were incorrectly drawn, most EPF arrows started from an appropriate source.

Table 33. Participant #01 described the oxygen-carbon bond-breaking. The participants' markings are in black. The researcher's labels in red indicate EPF arrows.

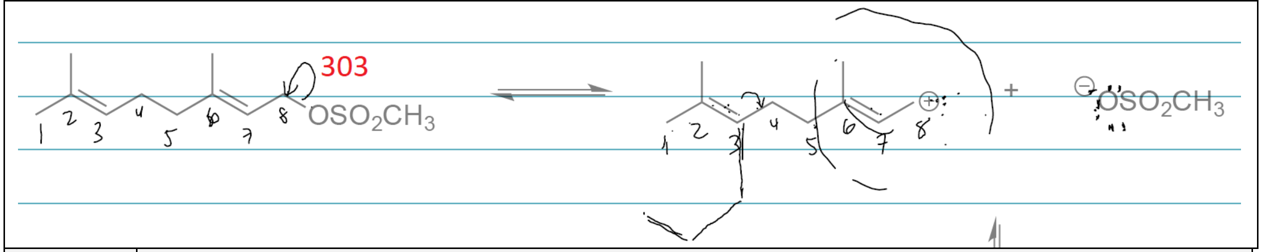
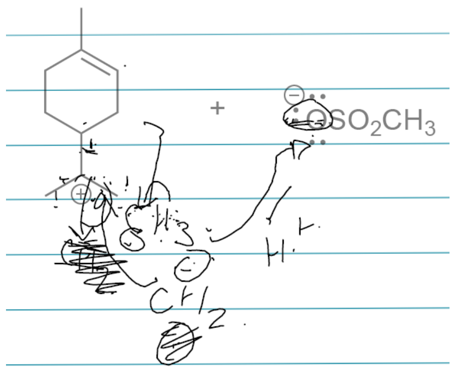
Question 3 Step 1 of 3	
	
#01:	*"This compound is broken down into two, which means […] where it's broken it's broken on the oxygen and the carbon so then the bond is going to go to the carbon so that you break that bond. Okay so yes the bond between carbon and oxygen breaks. Carbon becomes charged and yes that makes sense."*

Table 34. Illogical EPF arrows starting from the oxygen atom and pointing to the carbon-carbon bond or the positively charged carbon atom drawn by participants #02 and #05, respectively. The participants' markings are in black. The researcher's labels in red indicate EPF arrows.

Question 3 step 3 of 3	
Illogical EPF arrow pointing to the carbon-carbon bond	
	
Int:	*"So can we go through it one more time,* ***so the electrons from the oxygen"***
#02:	***"Move to bond*** *[arrow 323]* ***between the two carbons over here. And that created the double bond****."*
Illogical EPF arrow pointing to the positively charged carbon atom	
	
#05:	*"I feel like these electrons here, the like another set with oxygen should have something to do with the double bond as well because um it needs to get rid of two pairs in order to have no charge."*

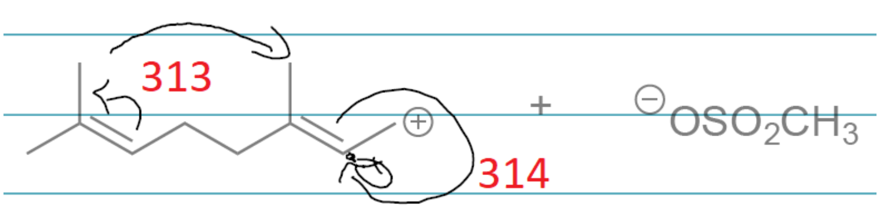
Table 35. Participant #08's drawings of cluttered illogical EPF arrows for question 3, step 3 of 3. The participants' markings are in black.



Section 3.16: Summary

Every participant similarly approached questions 2 and 3 by comparing surface features between the reactants and products. Participants compared electrons, atoms, bonds, or charges as an initial strategy, demonstrating that they were thinking at the submicroscopic level regarding their drawn EPF arrows. Although every participant approached questions 2 and 3 in the same manner, the drawn EPF arrows differed. While working on question 2, participants focused on comparing surface features between the reactants and products. However, participants demonstrated they did not see the implicit methylene group when comparing surface features. While working through question 3, participants compared surface features for each reaction step and were generally successful with the bond-breaking EPF arrows but found bond-forming EPF arrows challenging.

Table 36. EPF arrows are drawn from an appropriate electron-source, which follows instructions in lecture.

Electron Movement
"*I interpreted like the movement of electrons in particular from the arrows*."

Instruction: EPF arrows must be drawn from electrons and point to an atom or bond[1]

Participants demonstrated they were thinking about the EPF arrows regarding electron movement and bond-forming or breaking processes. Participants drew the start of the EPF arrow, but found drawing the arrowheads challenging. Participants recently learned about the EPF and drew their EPF arrows from an appropriate electron source, demonstrating they understood electrons are required and were comfortable with the arrow tail as a symbolic representation and as a retrieval of appropriate knowledge from their long-term memory. Participants faced difficulty with the arrowheads as the arrowhead generally did not point to an appropriate location. The incorrect arrowhead location could be due to an inability to retrieve appropriate knowledge from their long-term memory resulting in the incorrect interpretation.

Section 3.17: Concerted and stepwise interpretations

I analyzed participants' concerted and stepwise interpretations of the EPF arrows in this section. The correct interpretation of the EPF arrows is concerted where the EPF arrows occur simultanouesly within a givin mechanistic step. The incorrect interpretation of the EPF arrows is stepwise where the EPF arrows occur one at a time within a given mechanistic step. The interviewer asked all participants whether the EPF arrows occurred one at a time or all at once (Figure 10). Although participants held a certain visualization, nine participants described using a stepwise problem-solving approach to understand the EPF arrows and how the reaction proceeds. Examples of each type of understanding are in Appendix 15. I used research question 2 to guide this analysis section.

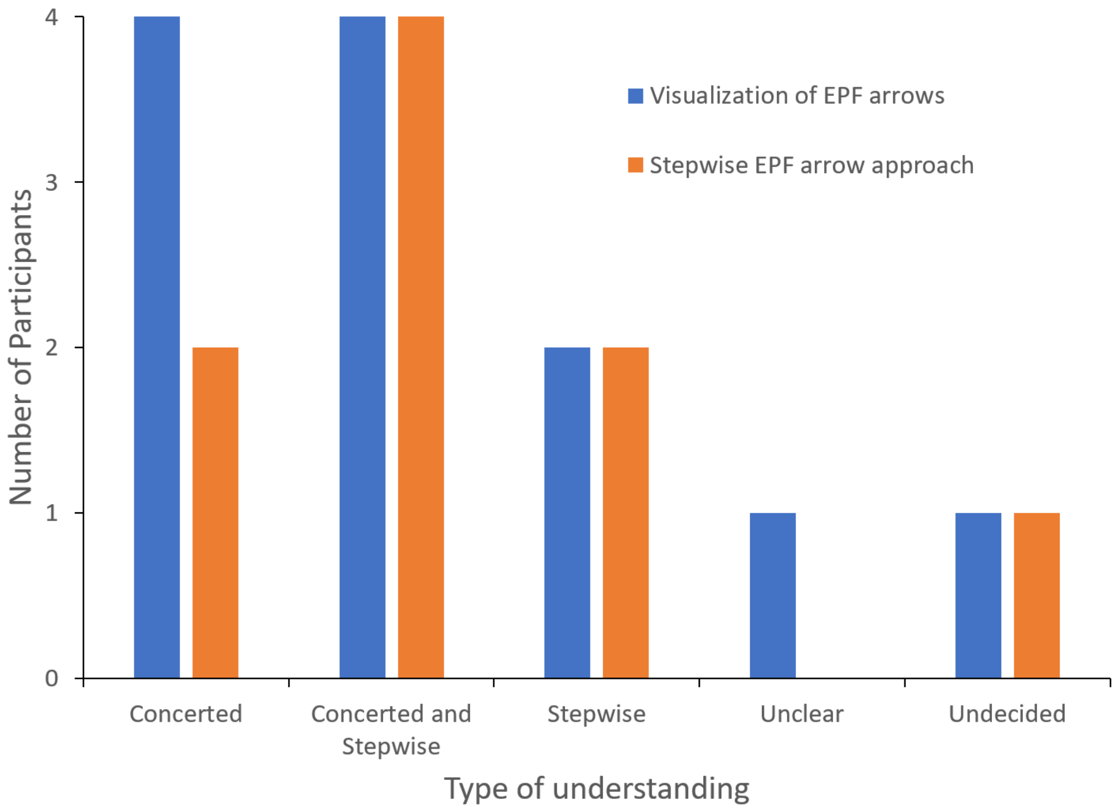


Figure 10. Participants' visualization and stepwise problem-solving approach to the EPF arrows (N = 12).

Section 3.18: Problem-solving using a stepwise approach

Most participants approached the EPF arrows stepwise as a method of interpretting and problem-solving. The interviewer asked whether the EPF arrows occurred at the same time or in steps and nine out of twelve participants described using a stepwise approach to interpret and problem-solve the EPF arrows. Five of the nine participants described interpreting the EPF arrows stepwise as easier for them to understand. For example, participant #01 explained that they believed the EPF arrows occurred all at once but found it easier to do it step by step (Table 37). Similarly, participants #07 and #12 described understanding that the arrows occur in a concerted manner but interpreted the EPF arrows singularly as it was easier (Table 37). Participant #12 included that interpreting all EPF arrows at once was too much and that a stepwise approach to the EPF arrows allowed them to visualize what was happening (Table 37. All participants' discussions of approaching the EPF arrows stepwise as easier are in Appendix 16.

Table 37. Participants #01, #07, and #12 described interpreting the EPF arrows stepwise as easier versus concerted.

Interpreting EPF arrows singularly is easier than concertedly

Int:	*“Okay to recap, does it happen at one time or all at once, or* ***do you think one arrow happens and then the next?****”*
#01:	***“I think it happens all at once, but to make it easier, it would be easier to do it step by step.****”*
Int:	*“Okay, okay sure um, so do you think that there’s an order to those four arrows that you drew?”*
#07:	***“The four is just a way to process the way I think, it makes it much more, I guess, organized and easier to think of*** *but it my head it probably, it just happens spontaneously at the same time.****”***
#12:	*“I just picture them going so from what you have first, so generally like on the left side going to the right side and then coming backwards.* ***But I do know that they’re technically supposed to be happening simultaneously****, but like in my head I just always pictured going from one to the other and then back […]* ***because it helps, I guess, um me to better visualize, like what is happening*** *[…] because* ***if I picture them at the same time then I get them all mixed up with the electrons*** *[…]* ***it’s just too much at the- like at once****.”*

Participants demonstrated using a stepwise approach to the EPF arrows to understand the reaction and to give the EPF arrows a purpose. For example, participant #06 held a concerted interpretation but interpreted the EPF arrows stepwise to problem-solve the reaction (Table 38). Participant #06 interpreted an EPF arrow which gave a reason for the next EPF arrow (Table 38). The order in which arrows occurred did not matter as participant #06 demonstrated they could interpret the EPF arrows in any order and described their method of understanding the EPF arrows as a tool to understand the EPF arrows (Table 38). Other participants used a similar approach by interpreting a singular EPF arrow as a representation, giving the following EPF arrow purpose. For example, participant #04 used a stepwise approach to understand how the reaction proceeded and drew a positive charge to represent the result of EPF arrow 602, which gave EPF arrow 601 a purpose (Table 39).

Table 38. Participant #06 described their stepwise interpretation to understand how the reaction occurs while knowing the EPF arrows occur in a concerted manner.

Question 1 step 3 of 4

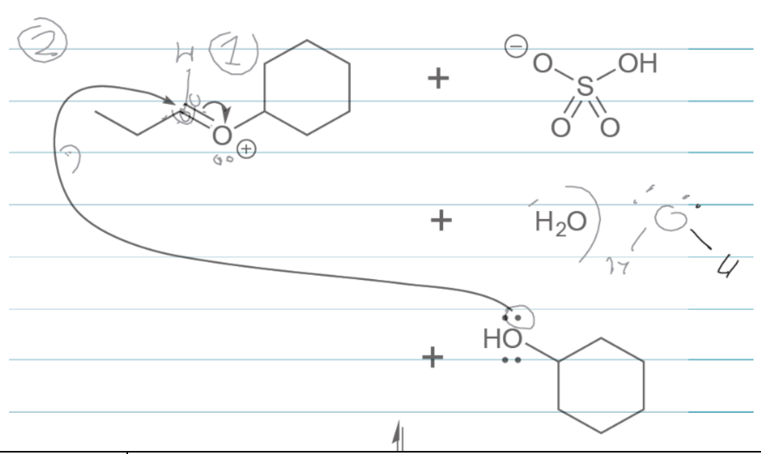
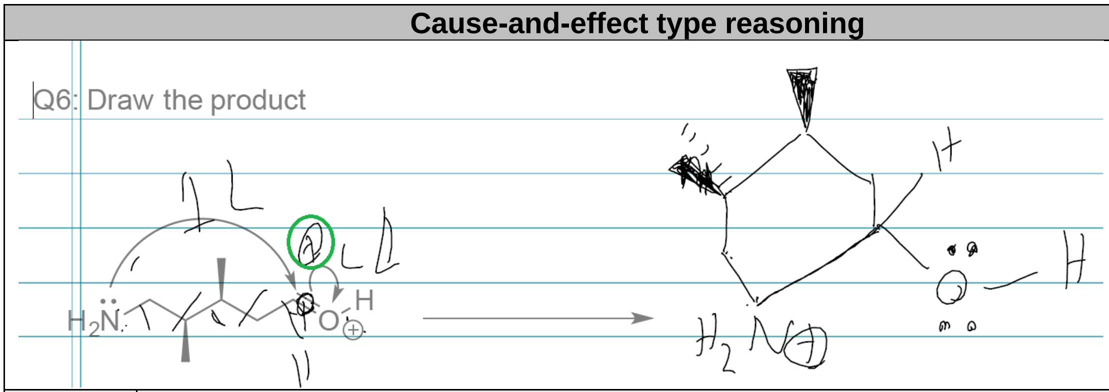
 	
#06:	*“**I kinda do it step by step with multiple arrows**… **Just to help myself understand it**,* […] ***I’m pretty sure they’re supposed to happen almost simultaneously if it’s shown in the same step**… But usually the way it happens is I, the first arrow that I decipher… How it works, **I just think oh okay that that that’s number one, that happened first, and then the next arrow I look at number two, why is it happening and what is happening**... But the- it could be either or, like um for instance in this case if I look at this arrow* [arrow 2] *… As number one, I’d just see okay so it bonds here, the carbon is electronegative, it doesn't like being electronegative so it, this bond here breaks* [arrow 1] *and then the valence pair goes to the electropositive oxygen, uh it, it works either way, it’s just again whichever one I happen to decipher first… […] **I see it in my mind when deciphering it as it being first step, second step, for two arrows are first step second step, third step for three arrows**, … **But that’s that’s just a tool I use I guess** ... **To figure it out**.”*

Table 39. Participant #04 described one arrow must occur before the other due to the creation of the positive charge. The researcher’s labels in red indicate EPF arrows. The researcher’s labels in blue indicate molecular species. The researcher circled the positive charge in green.

Question 6 – Stepwise interpretation	
 	
Int:	*“I was going to ask about the order of the arrows this time, if one happens before the other one or if they happen at the same time.”*
#04:	*“I think, yeah I think ‘cause I saw that positive charge first I kind of figured, the elec- those- the electrons would move there first* [Arrow 602] *and then the second positive charge is made* [Circled in green], *and then that would- the electrons would move* [Arrow 601]. *Or else like the electron kind of doesn’t really have a reason to move, there’s no positive charge on the carbon.”*

Similarly, participant #03 used a stepwise approach where one EPF arrow provides purpose for the next EPF arrow. Participant #03 emphasized the reaction occurring stepwise through their discussion and drawings of the EPF arrows in a “chain reaction” where one EPF arrow causes the next EPF arrow (Table 40). The drawings contained a positive charge (Table 40 circled in green), noting the positive charge is on the same carbon atom as participant #04 (Table 40 circled in green). Participant #03 described two interpretation orders of the EPF arrows. The first interpretation described the electrons on the nitrogen atom would only bond with the central carbon if there was a positive charge (Table 40). The second interpretation is if the nitrogen bonds to the carbon atom, it would have five bonds resulting in a negative charge and would break the octet rule, which would be the reason for the next EPF arrow (Table 40). The participants approached the EPF arrows by interpreting a singular EPF arrow which gave a reason for the next EPF arrow, describing a cause-and-effect of the EPF arrows to understand how the reaction occurs (Appendix 17). The other three participants held a concerted understanding or were not explicit in their discussion.

Table 40. Participant #03 described their problem-solving strategy where one EPF arrow gives a reason for the next EPF arrow. The participants’ markings are in black. The researcher circled the positive charge in green.

Cause-and-effect type reasoning	
	
Int:	*“I know in some of the previous questions I’ve asked you about. Do the arrows happen sequentially or at the same time? Is there an order to the electron movement here?”*
#03:	*“The carbon then wants to become neutral. And I would assume it would pull the nitrogen. Because it has a positive charge [circled in green][…] So then either way it could happen in either order. Like it could be the first step then this, or this be the first step then this… I don’t think it can happen at the same time ... because I think that it should be one happens and then it must happen. More of a chain reaction rather than boom. And it’s all done… I feel like this causes that, or this causes that.”*

Two participants verbalized numbers and the arrows, but the participants were not explicit enough. Their numbers could be interpreted as order of operations or that there were two arrows. Thus, participant #09 was labelled unclear (Table 41). Participant #13 described interpreting the

EPF arrows one at a time but did not know whether the reaction occurred simultaneously or stepwise and was labelled undecided (Table 41).

Table 41. Unclear and undecided interpretations.

Unclear	
Int:	*“Do you think um that the curved arrows um happen at the same time […] how it happens in your mind, um how do you think about that?”*
#09:	*“Yeah, there’s there should generally be two,* ***I think if not always there’s going to be the first curved arrow and then the second so um the first one****, especially if I’m looking at this, comes right from a pair of electrons… And then it goes to either a bond or molecule itself, and then, and then this is not scientific but from there* ***there’s gonna be a second arrow*** *that doesn’t r- it’s always shorter, you see.”*
Unclear	
Int:	*“Do you think that it happens in that order in your mind, or is it, let me just pick the one to start with first?”*
#09:	*“Well um, I know that that is, remember when we talked about,* ***there were like first and second arrows****?..* ***I’m pretty sure that that’s the second arrow****… Um and I don’t think* ***I should start with that one, because we always start with the first one, but I don’t know it’s just easier for me to see because there were electrons right there****.”*
Undecided	
Int:	*“So if you’re picturing this happening in your mind um do you think that what’s going on in each step is happening simultaneously or do you picture it kinda happening sequentially, one after the other?”*
#13:	*“****I think, in my head to make the problem easier I picture it happening one at a time****, like I picture if... Oh well if these electrons move here then we have to flow these here…* ***But I don’t know whether it, like in real time if it would happen all at the same time or not****.”*

Section 3.19: Contextual interpretations of the interview

Participants described specific interpretations for certain questions, summarized in (Figure 11). Contextual factors may have played a role in these questions. For example, question 1 was an explanatory question where participaants were given everything, including reactants, products, and EPF arrows, with interpretations being mainly concerted (Figure 11). A stepwise interpretation was prominent when looking at questions 5 and 6, where participants drew the final product when given the reactants and EPF arrows and reactants (Figure 11).

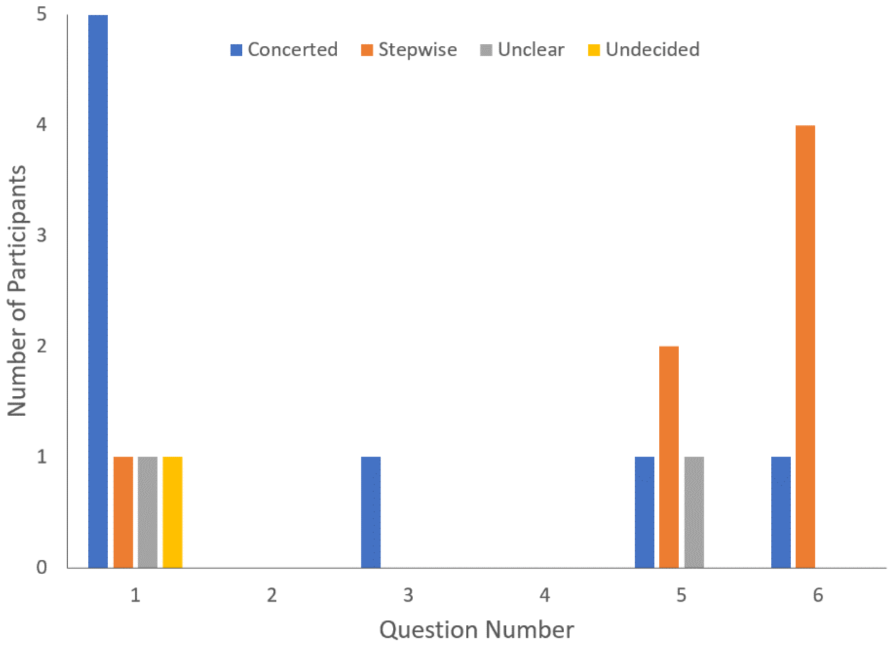


Figure 11. Participants' interpretation of the interview questions.

Four participants described a concerted interpretation and a stepwise interpretation when asked a second time. The interviewer prompted some participants twice on their interpretation of question 1 and questions 5 or 6. While the participants were working through question 1, the interviewer prompted four participants who describe a concerted interpretation of the EPF arrows. The interviewer prompted the same four participants again while working on questions 5 or 6, and the participants described a stepwise interpretation of the EPF arrows. For example, participant #03 initially described in question 1 that the EPF arrows occurred in a concerted manner (Table 42). However, while working on question 6, participant #06 held a stepwise interpretation where one EPF arrow must occur before the other. Similarly, participants #03 and #12 described the stepwise process as a chain reaction where one EPF arrow is the reason for the next EPF arrow (Table 42). All responses starting with concerted and stepwise interpretations are in Appendix 18.

Table 42. Participant #03 described their concerted and stepwise interpretations. The participants' markings are in black.

Concerted and Stepwise interpretations
Question 1 — Concerted

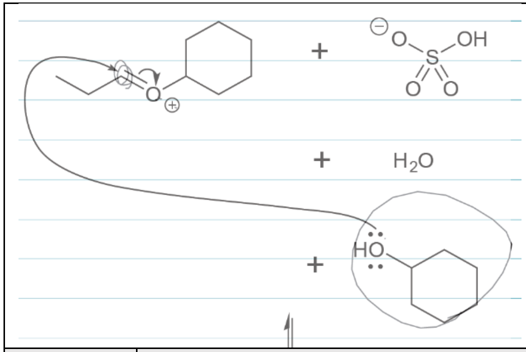
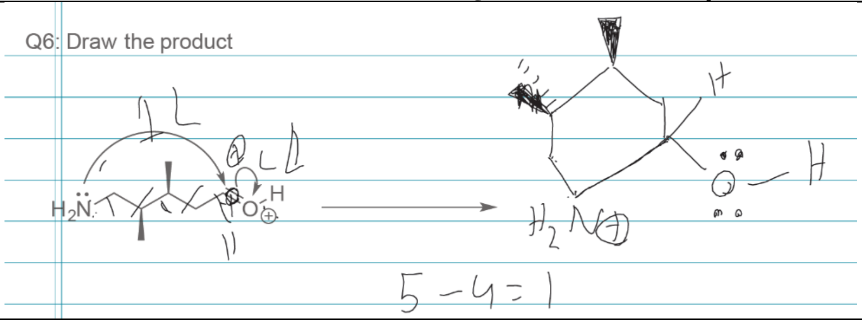
	
Int:	*“**Do you picture that in your head happening one after another**?”*
#03:	*“**I guess it would have to happen at the same time** I guess, because like simultaneously I guess the double bond. **The carbon can’t have more in its octet. So as it is happening, that has to happen simultaneously**. I would think. **So it doesn’t screw up with the octet rule**.”*
Question 6 — Stepwise	
Q6: Draw the product	
Int:	*“**Do the arrows happen sequentially or at the same time**? **Is there an order to the electron movement here**?”*
#03	*“**I guess for one thing to happen, one thing has to happen first**. So like for this, the double bond here to break and give oxygen two electrons or […] **then that would make this happen. So then either way it could happen in either order. Like it could be the first step then this, or this be the first step then this… yeah**. **Because I don’t think it can happen at the same time**?... because **I think that it should be one happens and then it must happen**. **More of a chain reaction** rather than boom. And it’s all done… **I feel like this causes that, or this causes that. I don’t know which one.**”*

Table 43. Participant #12 described the EPF arrows occurring in a chain reaction.

Stepwise	
Int:	*“Do you think that these happen in a order, I mean they’re all in one step here, but do you think that there’s a secret to them, or that in reality they happen at once but we just draw them one at a time?”*
#12:	*“**I think to a certain degree there has to be um, some steps because you can’t have just everything going on at once. Um but I think it like happens really really fast, so it seems simultaneous, um but something has to start the, the reaction because um**, I don’t think there’s anyway from them to know, just like okay so all of us at once, like all the electrons are just going to move (interviewer laughs), um and it’s going to work out. **So something has to start it, and then from there it’s like a chain reaction of what happens.**”*

Section 3.20: Summary

In this section, I looked at whether participants' interpretations were concerted or stepwise with respect to the EPF arrows. The interviewer asked participants whether they thought the EPF arrows occurred one at a time or at the same time within a given reaction step. I split the participants' interpretations between how they visualized and approached the EPF arrows. Participants' visualized the EPF arrows stepwise or concertedly (Appendixes 19 & 20). Contextual factors of the questions may have played a role as concerted visualization was prominent in question 1, while stepwise visualizations were prominent in questions 5 and 6. The majority of participants approached the EPF arrows stepwise as they explicitly described interpreting the EPF arrows singularly as easier for them to understand how the reaction occurred. Participants used a common reason for the stepwise interpretation, cause-and-effect, to give the EPF arrows a purpose, where one EPF arrow gives a reason for the next EPF arrow. Participants retrieved information from their long-term memory to interpret a singular EPF arrow, resulting in the purpose for the next EPF arrow. Participants chose which EPF arrows to interpret based on their prior knowledge. Participants' prior knowledge included electron movement arguments (charges, bonds, or stability), demonstrating the participants were thinking about the EPF arrows at the submicroscopic level and as a symbolic representation.

Section 3.21: Transplanting electrons

Transplanting electrons is an error described as electrons being picked up and relocated onto a different atom (Flynn and Featherstone, 2017). To review the transplanting error, please see Section 1.8: Transplanting electrons.

This section explores why participants transplanted electrons with the frequencies summarized in Figure 12. Questions 1 to 3 of the interview did not have any transplanting errors because participants were not given an opportunity to transplant due to the products being given. Participants had to interpret the EPF arrows and draw a product While working on questions 4 through 6. I observed two different types of transplanting electrons in the data. While working on question 4, a non-adjacent bond was transplanted; on questions 5 and 6, an electron pair from the nitrogen atom was transplanted onto a carbon atom. I used research question 2 to guide this analysis section.

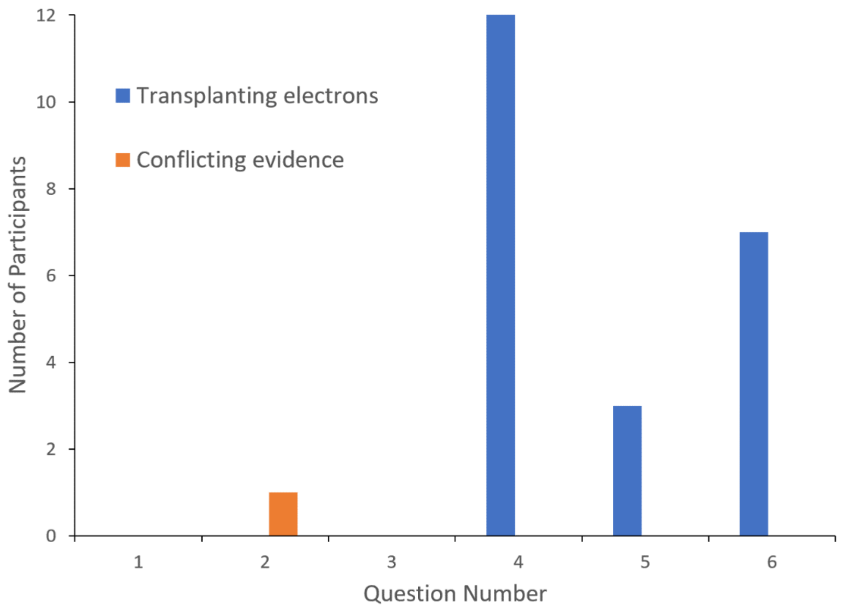
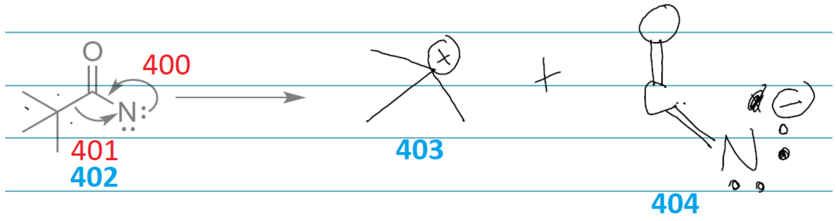


Figure 12. Frequency of when participants described transplanting electrons. (N = 12).

Section 3.22: Similar transplanting approach

Every participant approached question 4 by interpreting EPF arrow 401 as bond-breaking (Table 44). Every participant described the same carbon-carbon bond-breaking with the electrons moving onto the nitrogen atom. For example, participant #13 described the carbon-carbon bond-breaking with electrons moving onto the nitrogen atom (Table 44). All of the participants' responses regarding transplanting electrons in question 4 are in Appendix 21. The consistent descriptions of the same carbon-carbon bond-breaking demonstrate a similar thought process, suggesting each participant interpreted EPF arrow 401 similarly. The transplanted products contained two oppositely charged atoms demonstrating participants transplanting interpretation. All participants with the same two oppositely charged atoms for question 4 can be found in Appendix 22.

Table 44. Participant #13 described the electrons from the carbon-carbon bond moving onto the nitrogen atom. The participant's markings are in black. The researcher's labels in red indicate EPF arrows. The researcher's labels in blue indicate molecular species.

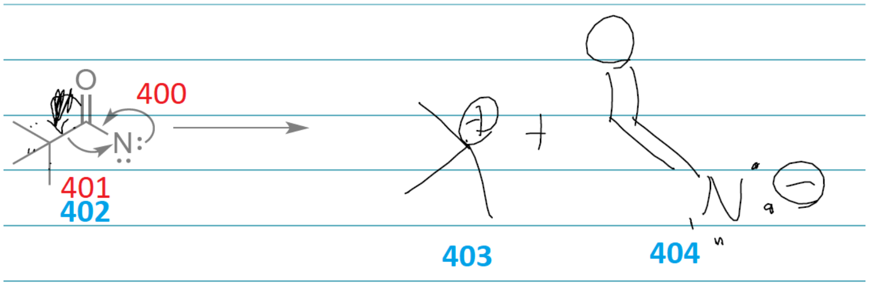
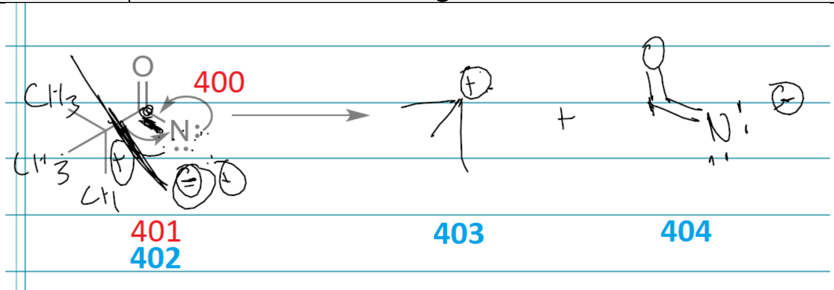
Participant #13 — Question 4


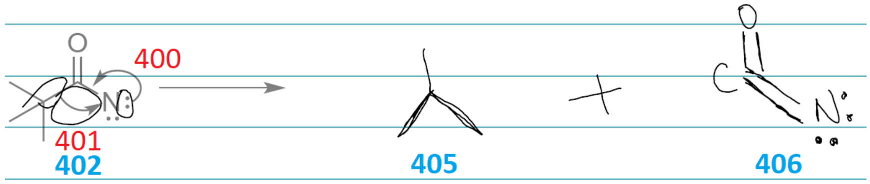
#13:	*“Nitrogen is giving electrons to this bond [Arrow 400], which will, which would normally form a, so that would form a double bond. And,* ***but this bond is breaking*** *[arrow 401]* ***and giving electrons to the nitrogen.****”*

Section 3.23: Reasons for transplanting

Two participants gave their interpretation of why they believed EPF arrow 401 was bond-breaking, which might explain all participants’ responses (Table 45). Participant #03 described their interpretation of the EPF arrow 401, where the EPF arrow pointing from the bond-to-atom indicates a bond is broken (Table 45). While participant #08 described that electrons must move in pairs resulting in both electrons from the carbon-carbon moving onto the nitrogen atom (Table 45). Most participants correctly declared the carbon-carbon bond as bond-breaking but did not see the carbon-nitrogen bond-forming, resulting in the transplanted electrons on the nitrogen atom. For example, participant #07 declared that the bottom EPF arrow 401 is bond-breaking with the electrons moving onto the nitrogen (Table 45). The participants who declared EPF arrow 401 as bond-breaking might have held the same ideas as participants #03 and #08, where EPF 401 is interpreted as bond-breaking due to the EPF arrow pointing from a bond-to-atom.

Table 45. Participants #03, #08, and #07 interpretations of EPF arrow 401. The participant’s markings are in black. The researcher’s labels in red indicate EPF arrows. The researcher’s labels in blue indicate molecular species.

Question 4	
	
#03:	***“So this arrow*** *[Arrow 401]* ***shows to this bond is breaking because an arrow from a bond to an atom breaks the bond, giving that atom the two electrons*** *[Molecule 404]. […]* ***that bond doesn’t exist anymore because it’s giving it’s electrons to the nitrogen****.”*
	
#08:	***“We should look at this bottom arrow*** [Arrow 401 circled in red]. ***Which is actually breaking a bond here****. […] I guess it’s just something we learned.* ***You can’t really***

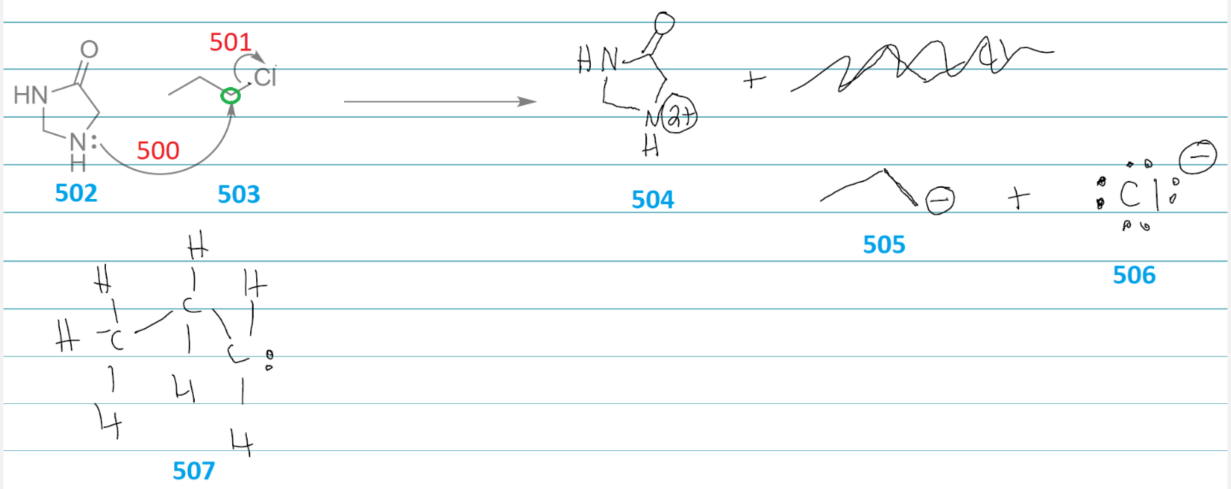
	take electrons out of a bond and still have the bond be there. ***Cause like a single bond is two electrons and whenever you are moving electrons, you are always moving two***. ***You can’t move one at a time***. *And so you can’t take one electron out and have half a bond*. ***So you need to like, break the full bond apart*** [Black line labeled 407] ***to get those electrons out to make the lone pair on the N*** *[Molecule 406].”*
	
#07:	*“**The curved arrow, the first on the bottom** [Arrow 401]* ***it mo- definitely moved the bond either the bond.**.. I might have drawn this incorrectly or not sure.* ***But it moved the bond- broke the bond and the bond became an electron and attached to the nitrogen****. And the- this large higher curved arrow [Arrow 400] took the electrons and create- turned into a bond that connect to the central carbon atom. […] I mean it was pretty straight forward.* ***The bond broke and then you move electrons over to create two compounds*** *[Molecules 405 and 406].”*

Section 3.24: Electron pair to atom transplanting

I observed another form of transplanting error in questions 5 and 6. Participants took a lone pair of electrons from the nitrogen atom and placed them onto a carbon atom as their interpretation of the EPF arrows. For example, participant #02 described EPF arrow 500 as the lone pair from the nitrogen atom being transferred onto the specific carbon atom (Table 46 circled in green on molecule 503), resulting in the transplanted electrons on molecule 507 and the two positive charges on molecule 504 (Table 46). The interviewer prompted participant #02 on whether any bonds were forming, where participant #02 replied they did not see any bonds forming, only bonds breaking (Table 46). Similarly, in question 6, seven participants described EPF arrow 600 as the electron pair on the nitrogen atom transferring onto the specific carbon atom. For example, participant #09 was confident when transplanting the electron pair from the nitrogen onto the carbon atom (Table 47). All participants transplanting responses for questions 5 and 6 are in Appendix 23. The participants who transplanted electrons might have held the same interpretation as participant #02, where they did not see any bond-forming EPF arrows.

Table 46. Participants #02’s transplanting interpretation for EPF arrow 500. The participant’s markings are in black. The researcher’s labels in red indicate EPF arrows. The researcher’s labels in blue indicate molecular species. The green circle represents where the transplanting error occurred.

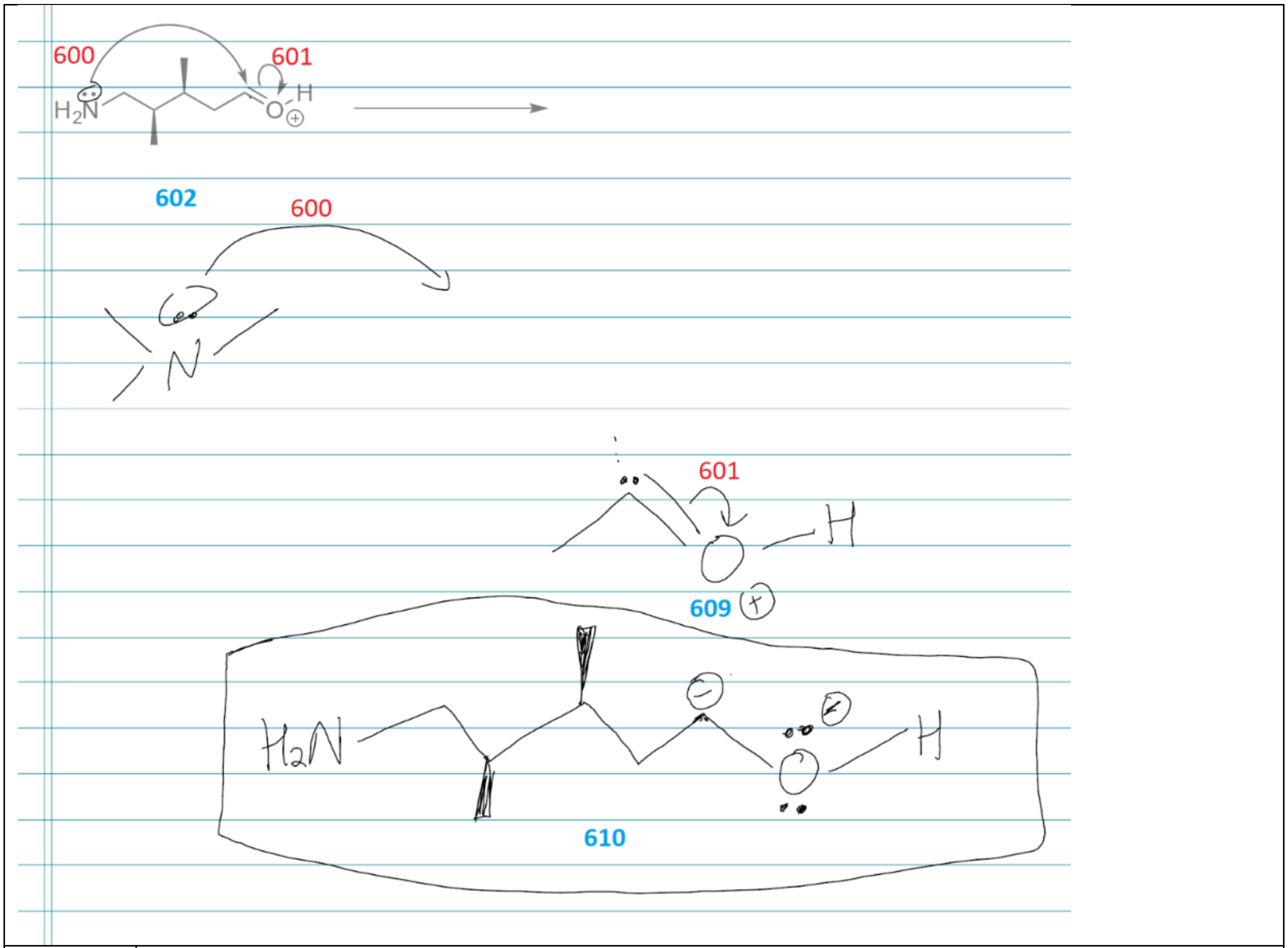
Question 5



Int:	*“Talk me through how you knew the electrons were going to be transferred. Or this lone pair is going to be on this carbon [circled in green on molecule 503].”*
#02:	*“**From the arrow** [Arrow 500]. **The lone pair from the nitrogen are going to be transferred to that carbon specific**. […] The electrons would be pointing. The arrow here would be pointing towards the bond.”*
Int:	*“What told you here that any bonds were being broken or formed. I don’t know if we have any bonds forming.”*
#02:	*“**I don’t see any bonds forming, but breaking here was the bond here from this arrow** [Arrow 501] **to this chlorine**. And yeah. That would have made it. **Broken the bond instead of the electrons being on the carbon will be on the chlorine** [Molecule 506].”*

Table 47. Participant #09’s transplanting interpretation for EPF arrow 600 on question 6. The participant’s markings are in black. The researcher’s labels in red indicate EPF arrows. The researcher’s labels in blue indicate molecular species.

Question 6

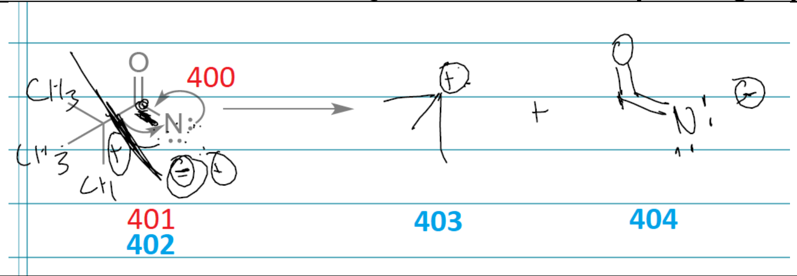
	
#09:	*“Okay,* ***so we’ve got a pair of electrons from the nitrogen****, […]* ***so this pair of electrons I’m assuming is, it wants to go away so that’s why it’s leaving via the curved arrows*** *[arrow 600], you can see, so* ***then it’s going to that carbon*** *[electrons circled in green on molecule 609] […]* ***But there’s already double bonds from there […] That means that the double bond needs to move*** *[…]* ***this arrow*** *[Arrow 601]* ***that comes to the oxygen*** *[…]* ***That’s going to break the double bond*** *and the oxygen is gonna have an extra one, two, three, four, and extra pair of lone pair, or not lone pairs, electrons, […]* ***And then you draw a negative charge there****,* ***I think that positive charge just disappears*** *[…]* ***When these electrons leave****,* ***that’s gonna be the way it is, I’m happy there****,* ***and I know that this is most likely what’s gonna happen with that double bond, with the negative charge, those pair of electrons****.”*

Section 3.25: Conflicting mental models resulting in transplanting electrons

I observed one participant with conflicting evidence regarding transplanting electrons. Participant #08 correctly described transplanting electrons are not possible while working on question 2, but transplanted electrons while working on question 4. While working on question 2, participant #08 correctly described that electrons could not be picked up and placed at will, but rather the electrons must travel through atoms (Table 48). While working on question 4, participant #08 demonstrated transplanting the electrons from the carbon-carbon bond onto the nitrogen atom

(Table 48 molecule 404). Participant #08 described that two electrons are required for movement and that a singular electron from the carbon-carbon bond cannot move as half a bond would form. Thus both electrons from the carbon-carbon bond move onto the nitrogen atom. Participant #08 demonstrated conflicting mental models where although they described transplanting electrons are not possible but transplanted as an interpretation of EPF arrow 401 (Table 48).

Table 48. Participant #08 described transplanting are not possible in question 2 and then demonstrated the transplanting process for question 4. The participant's markings are in black. The researcher's labels in red indicate EPF arrows. The researcher's labels in blue indicate molecular species.

Question 2 – Transplanting is not possible	
#08:	*"From what I understand like so like I can't just like, just pluck these electrons off and just like glue them on here […] yeah, you can't take them off of somewhere they have to move through […] they have move through other atoms"*
Question 4 — Transplanting is possible	
	
#08:	*"We should look at this bottom arrow [Arrow 401 circled in red]. Which is actually breaking a bond here. So we actually break these apart. So then this would become just a. methyl group […] You can't really take electrons out of a bond and still have the bond be there. Cause like a single bond is two electrons and whenever you are moving electrons, you are always moving two. You can't move one at a time. And so you can't take one electron out and have half a bond. So you need to like, break the full bond apart to get those electrons out to make the lone pair on the N [Molecule 406]."*

Section 3.26: Summary

In this section, I looked at participants' transplanting interpretations with respect to the EPF arrows. I observed two types of transplanting electrons errors. The first observed type of transplanting was participants taking the electrons from a carbon-carbon bond and placing them onto the nitrogen atom. The second observed type of transplanting was participants taking the electrons from the nitrogen atom and placing them onto the carbon atom. Participants picked up a pair of electrons in both transplanting interpretations and put them where the arrow pointed. Participant #03 described their interpretations of the EPF arrows, where an EPF arrow that points from a bond-to-atom breaks the bond. In addition, participant #02 said they did not see any EPF arrows that depict a bond-forming process when asked by the interviewer.

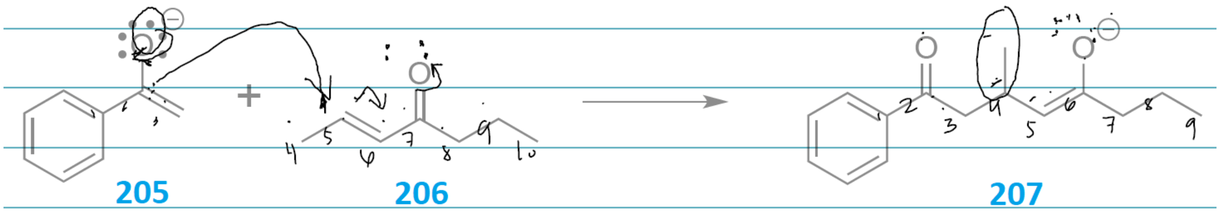
Section 3.27: Mapping strategy

In this section, I reviewed all participants' explicit mapping strategies ($n = 4$). All participants verbally mapped the structures through numerals. However, most were not physically labelled on paper, meaning participants' verbal mapping could not be coordinated onto any structure post-interview. Participants verbally counting could be interpreted in either direction, left-to-right or right-to-left, and could also be mistaken for participants counting electrons or bonds, thus making verbal counting unreliable to determine whether participants applied the mapping strategy. I used research question 2 to guide this analysis section.

Section 3.28: Effective mapping strategies

There were few instances of the mapping strategy, with one participant demonstrating the strategy's effectiveness. When mapping was observed, participants compared the carbon atoms between the reactants and products. For example, participant 01 compared the reactants and products by numbering the carbon atoms revealing an error in their drawn labels (Table 49). Participant #01, through their incorrect labels, determined the correct bond location by confirming the carbon atom labelled #4 on molecule 206 as the methyl group in the products (Table 49 circled in black molecule 207). Participant #01 determined that carbon #5 would be the reactive site and drew the correct EPF arrows (Table 49 molecule 206). Although participant #01 initially incorrectly labelled the atoms in the reaction, they used the mapping strategy to locate the bond location correctly and determined how to draw the correct EPF arrows, demonstrating how the mapping strategy can lead to the correct answer.

Table 49. Participant #01 demonstrated how mapping could lead to the correct answer through labelling atoms. The participants' markings are in black. The researcher's labels in blue indicate molecular species.

Question 2	
	
Int:	*"I think I understand, okay great, tell me about um the first thing I saw you do was um assign numbers to the carbons, what was going through your mind, what was your intentions with doing that?"*

#01:	*"I was wondering where this group came [cirled in black on molecule 207] from, so I wanted to make sure it wasn't the first carbon on the atom here [carbon 4 on molecule 206] that I was going to connect, make the bond to so by counting the numbers I find out , the carbon over there is going to make a bond to the second carbon [Carbon 5 on molecule 206] on this one, and that's [carbon 4 on molecule 206] what is going to cause this to stick out over here [circled in black on molecule 207] […] I saw this how it looks like in the product then it has to make a connection the first one the first one [molecule 205] has to make a bond with the second one [molecule 206] through this carbon [carbon 5 on molecule 206]."*

Section 3.29: Implicit atom error

Question 2 of the interview highlighted a difficulty participants faced when approaching implicit atom-type questions. When participants mapped the reaction, they incorrectly labelled the methyl group suggesting the participants did not see the methyl group. Figure 13 illustrates the missing methyl group (circled in black).

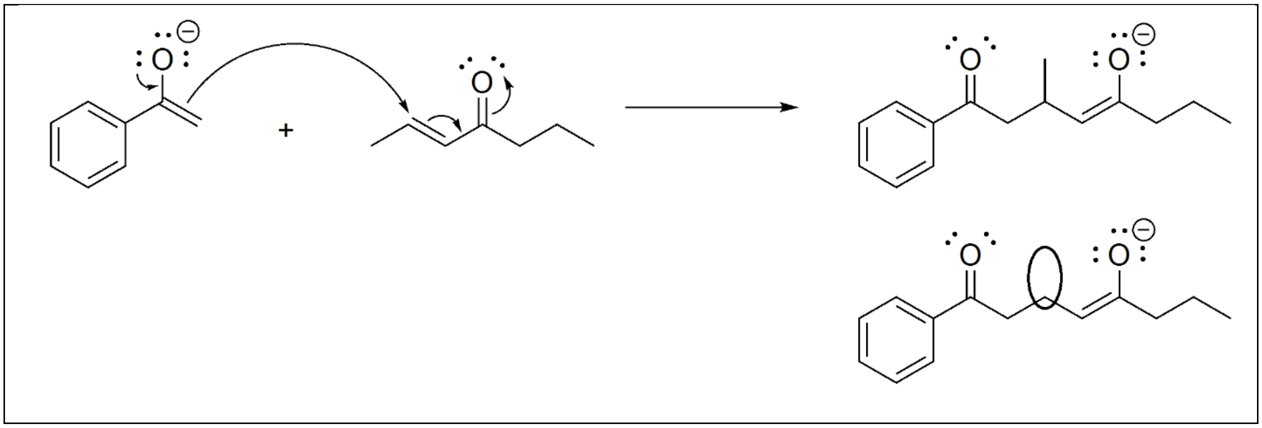
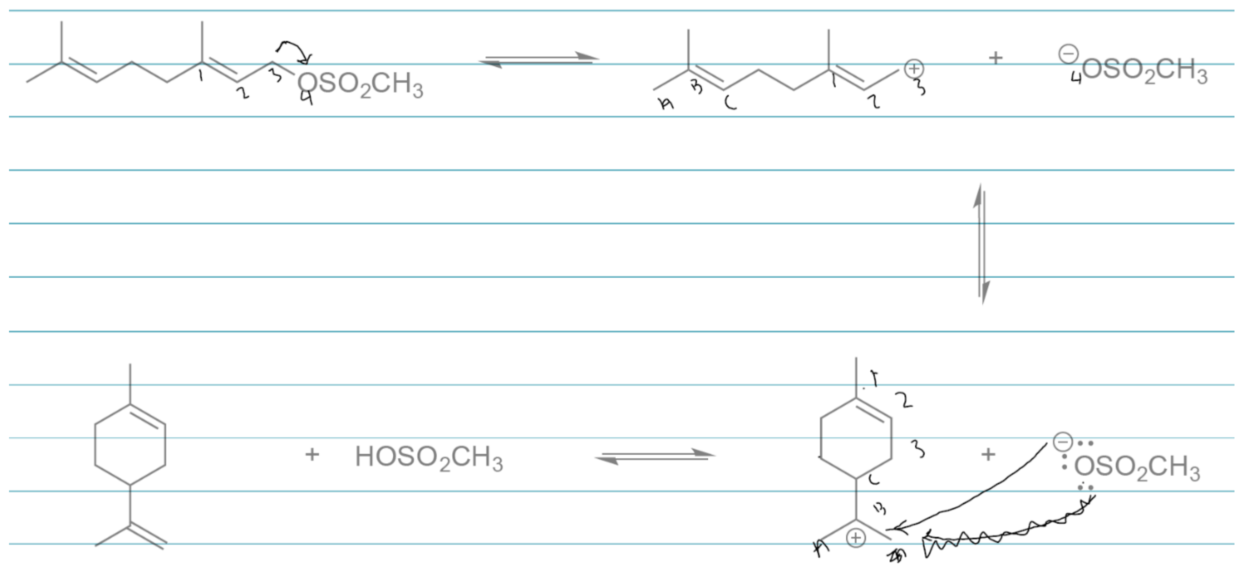


Figure 13. The methyl group circled in black is frequently not mapped correctly. The image is reproduced with minor edits From Carle, Visser, and Flynn ***2020*** with permission *from the Royal Society of Chemistry.*

Participant #11 focused on mapping carbon atoms in question 3 and faced difficulty with an implicit atom type question (Table 50). In the first step of question 3, participant #11 correctly mapped four atoms, the carbon and oxygen atoms and used mapping to determine how they would draw the EPF arrow accurately to complete the first step. Participant #11 initially skipped the second step and when they came back to it they included the alphabet to differentiate between the two alkenes (Table 50). Participant #11 could not draw an EPF arrow, although able to differentiate between the two alkenes through mapping the carbon atoms, and decided to move on.

Table 50. Participant #11 demonstrated the correct mapping for question 3, but could not provide EPF arrows for step 2. The participants' markings are in black.

Participant #11 – Question 3 – Correct Mapping



Question 3 Step 1 of 3	
#11:	*“Let’s say **because you break the bond the electrons goes from where you put 3 to 4**. That would cause, hum, **since you lose an electron that would cause a positive charge here**, and then since it’s- the oxygen here, **the whole oxygen thingy is gaining an extra electron to have the negative**.”*
Int:	***“Okay, so what kind of arrow would you draw to draw that”***
#11:	*“**Um it starts at** [inaudible] **3 and ends at** [inaudible] **4**”*
Question 3 Step 2 of 3	
#11:	***“I recognize something, I just don’t know how I would draw the arrows to show it.”***
Int:	*“Okay, what do you recognize?”*
#11:	*“**There is a double bond. But when you, it forms the cyclo part, the double bond is missing. And instead you have a positive charge.** I don’t know where the double bond would.”*
Int:	*“Okay Okay. Um, could you tell me something about how you decided that those were the same carbons?”*
#11:	*“**I labeled them one two so I’ll just label them one two again** […] **So my best guess would be the double bond at one two kind of stays there**, um, and for the positive on three and double bond from b,c a, not sure what happens to those two […] **I’m pretty much out of guess**.”*

Participants made assumptions in the reaction that led to errors. Participants #01 and #09 assumed that the first alkene in the reactant (rounded square in orange on molecule 350 in Figure 14), was the first alkene in the product (squared in green on molecule 353 in Figure 14), due to the section of the molecules looking identical. Both participants #01 and #09 demonstrated interpreting the first alkene in the reactant as the first alkene in the product through their numbering system for the second step of question 3. Both participants incorrectly mapped the second step of question 3, which might be due to interpreting the molecules from left to right. Participant #01 initially described the ring formation as an easy step and attempted several times to map the reaction preserving the alkene in the cyclic, but was unsuccessful and decided to move forward instead of reattempting the question (Table 51). Participant #09 mapped similarly to participant #01, where the alkene is preserved in the products (Table 52). Participant #09 described the differences between the reactant and the product but could not comprehend that the alkene in the product is the second alkene in the reactant (Table 52). Alternatively, participant #01 did not consider the second alkene as the preserved alkene. Participants #01 and #09 demonstrated reading the molecules from left to right as their mapping numerals increased from left to right in both the reactant and product (Table 51 and Table 52). Participants #01 and #09 assumed that the first alkene in the reactant would be the same in the product. Their assumptions in organic chemistry appeared to create a learning barrier as the assumptions are what caused the errors. Participants #01 and #09 displayed smaller aspects of the mapping strategy. Participant #01 described conserving atoms in the reaction by making sure there were no excess carbons, and participant #09 described reactive areas as the changes between the reactants and products.

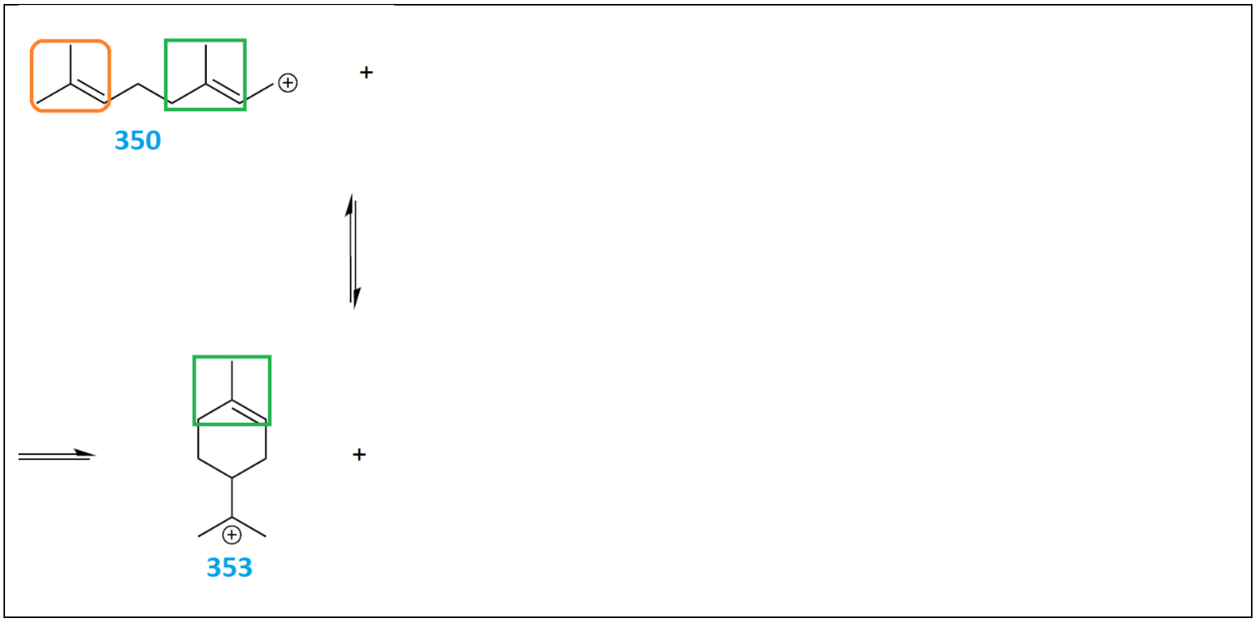
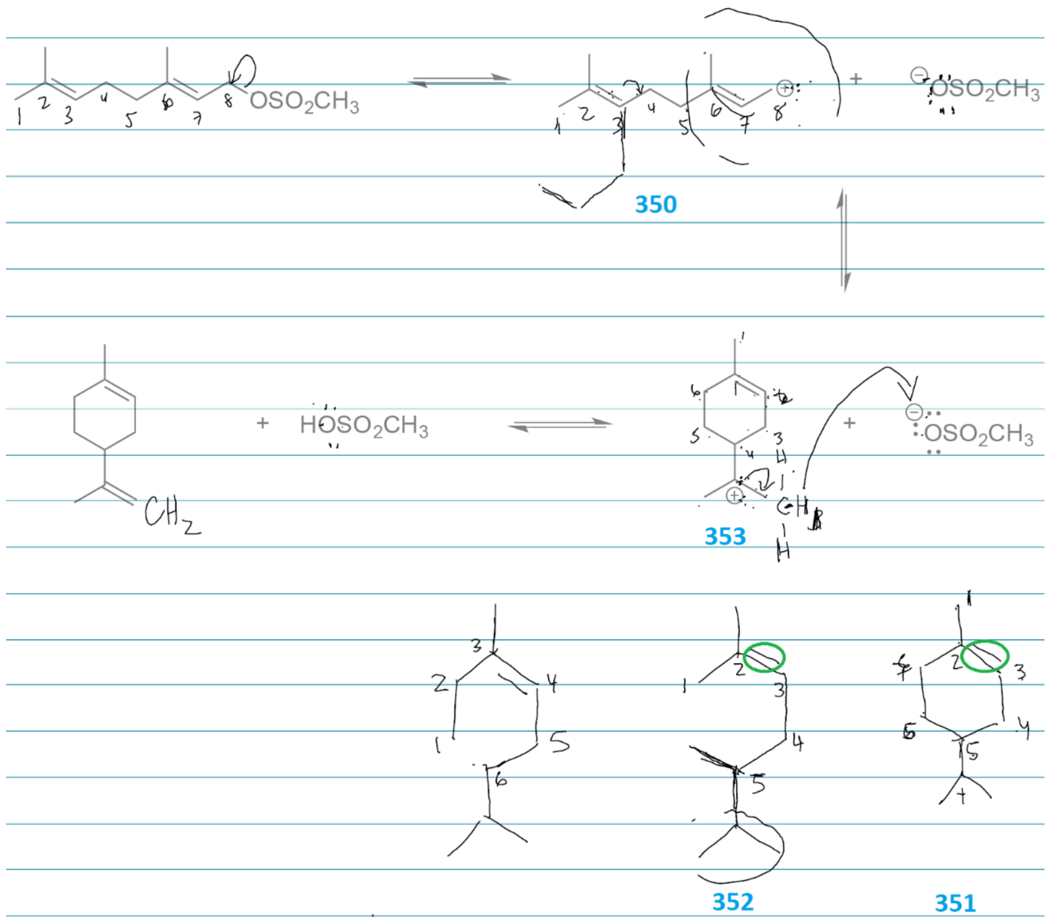


Figure 14. Similarities between the reactant and product for Question 3 step 2 of 3 (Molecules 350 and 353 respectively). The green box is translated onto the product, but participants assumed that the round orange box was the green box in the product.

Table 51. Participant #01 incorrect mapping for question 3, step 2 of 2. The participants' markings are in black. The researcher's labels in blue indicate molecular species. The researcher's circles in green indicate the same alkene.

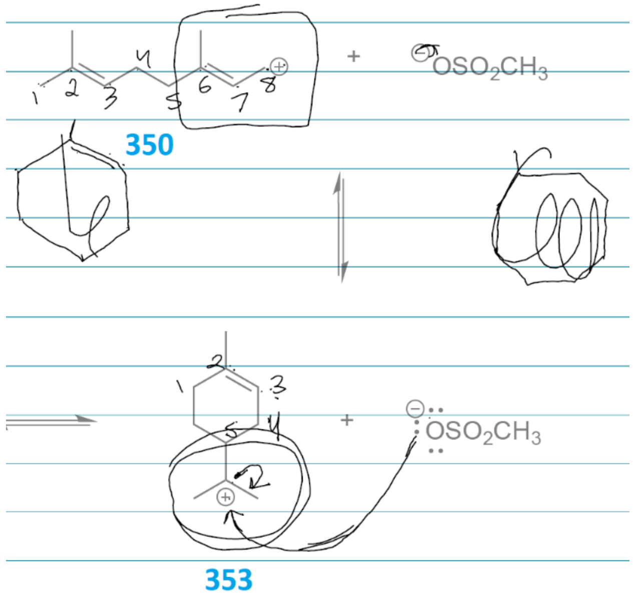
Question 3



Step 2 of 3 (incorrect mapping)	
#01:	*"So, so far, um the ring is easy to make because the double. Can I show you? Or do I have to explain them right? "*
Int:	*"Sure yeah, sure. How do you want to show me?"*
#01:	*"Um, **because I numbered it here one, two, three, four, so that means that it is basically. So the ring Is easy to make. So four is going to stick out here. Five is going to stick out like that. Six is going to go like that. And a problem is there is a double bond here** […] because **I have to figure out how that bond breaks and where the electron pairs move. And where to put the arrows**. **One two three four. Five. This is the part that really stumps me**."*
Int:	***"Are you counting the carbons to make sure there's the same number**?"*
#01:	*"**Mhmm that I'm not just going to make a random carbon**."*
Int:	*"Would you like to move onto the next step? We can come back to it?"*
#01:	*"Sure, that's what I should be doing maybe looking at the. Because I've been doing that earlier just looking at the products to see how it will end up. But. No I don't think we need to go back actually."*

Table 52. Participant #09 incorrect mapping for question 3, step 2 of 3. The participants' markings are in black. The researcher's labels in blue indicate molecular species.

Question 3 (step 2 of 3) – Incorrect Mapping

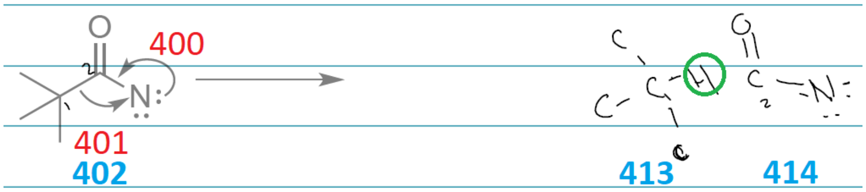
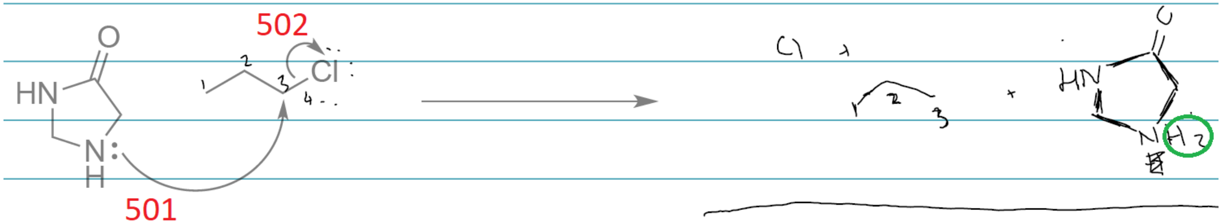


#09:	*“**I’m trying to figure out how the line diagram** […] **Became um a cyclic structure.**”*
Int:	*“[…] Okay, what helped you to decide that?”*
#09:	*“**Looking at this molecule** […] **For sure and then um well you can, so it had eight just the same** […] so that has six carbons in it, methyl group there, double bond, so one, two, three, four, five, six, but see **I don’t know how to make this** [circled in black on molecule 353.]”*
Int:	*“**What information would tell you how to draw the- in the curved arrows**”*
#09:	*“**The charge** […] **Double bond**, **um the loss of this molecule and then the gaining of this positive** […] **And I’m not sure how to draw** […] **Because the two three shares the double bond** […] And that’s there, and I can see that there, and then there’s **that methyl group which is consistent**, **so then four, five maybe and then somewhere here we lose a double bond.”***
Int:	*“**Okay, what tells you that?**”*
#09:	*“**There isn’t a double bond here** [circled in black on molecule 353] […] Now I’m not, **so yeah we lose the double bond**, how? That’s a good question, hmm, I’m wondering if this [*π-electrons *on molecule 353] is that [*π-electrons between *carbon 6 to 7 on molecule 350] and if the molecule’s- no that can’t be that […] **I don’t think that that arrangement can happen from that** […] **With these little methyl groups, I’m not sure** […] So (laughs) I’m gonna leave it there.”*

Section 3.30: Recalling information from a different course

Participant #11 recalled information from a different course and applied it to organic chemistry while working on questions 4 and 5 (Table 53). Participant #11 correctly mapped only the carbon atoms for questions 4 and 5, wherein participant #11 drew incorrect products in both questions. The products for both questions were incorrect due to transplanting electrons and excess hydrogen atoms. While working on question 4, participant #11 hinted that a hydrogen atom nearby would be taken but was not addressed. While working on question 5, participant #11 added an extra hydrogen atom, described as coming from the environment where hydrogen atoms are abundant, to stabilize atoms. Participant #11 was unsure whether their assumption was applicable and leveraged prior knowledge to compensate for their lack of organic chemistry knowledge. Although using ideas from other courses to help reinforce knowledge is a good idea, participant #11 incorrectly applied their prior knowledge resulting in an incorrect answer. The reasoning for the excess hydrogen atom in question 5 explains the extra hydrogen atom in question 4.

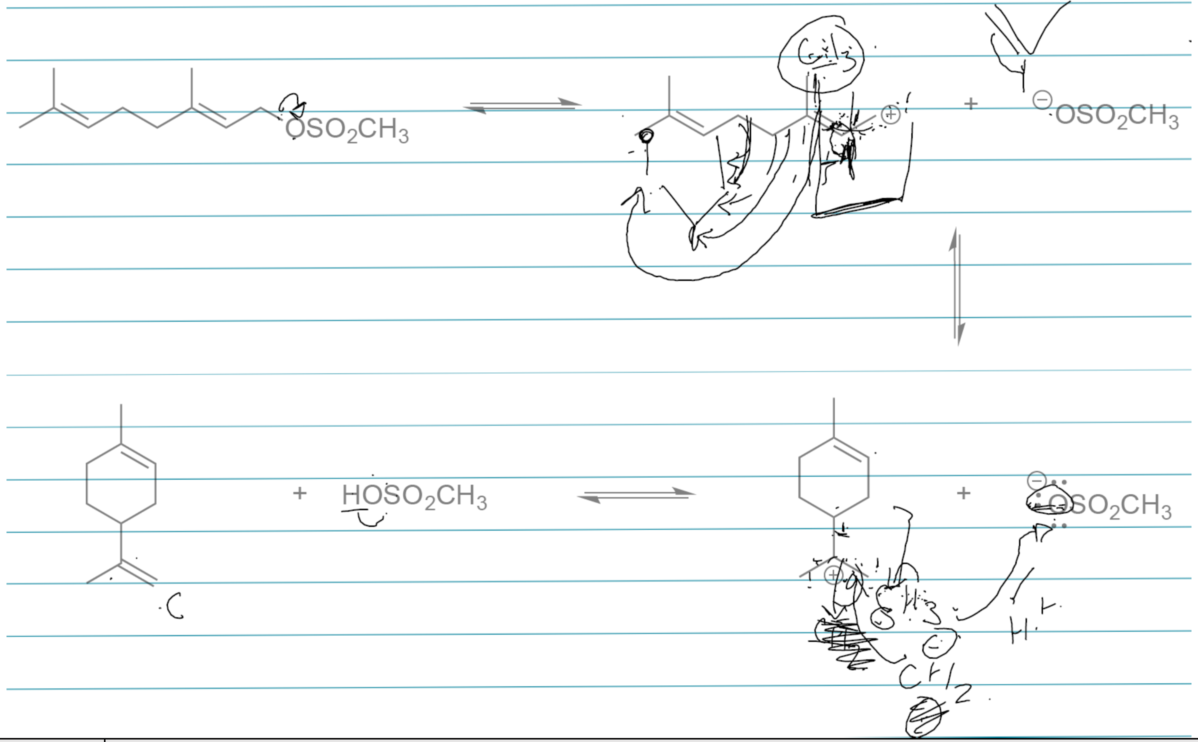
Table 53. Participant #11 demonstrated the correct mapping with incorrect products for questions 4 and 5. The participants' markings are in black. The researcher's labels in red indicate EPF arrows. The researcher's labels in blue indicate molecular species. The researcher circled the extra hydrogen in green.

<table>
<tr><th colspan="2">Question 4</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>#11:</td><td><i>"I am gonna label it [carbon atoms numbered 1 and 2]. So next thing should be the, um, the breaking arrow electron came from carbon two so carbon one still has some leftover and, I guess that would just be the hydrogen [Circled in Green] from somewhere nearby might be coming in."</i></td></tr>
<tr><th colspan="2">Question 5</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>#11:</td><td><i>"I am just labelling everything again […] I want to say an extra hydrogen comes in to fill the octet for nitrogen."</i></td></tr>
<tr><td>Int:</td><td><i>"Okay. Do you know where it might come from?"</i></td></tr>
<tr><td>#11:</td><td><i>"The outside?"</i></td></tr>
<tr><td>Int:</td><td><i>"Like the environment like you were saying before?"</i></td></tr>
<tr><td>#11:</td><td><i>"Yeah but, at this point I don't think that's right. […] Because I think when my teacher told me that he was talking about actually inside the cell because we were describing like electron transport chain and he's like well there is always a bunch of hydrogen so you can always just fill it in. So I don't think that's actually applicable to this."</i></td></tr>
</table>

Section 3.31: Mapping the electrons used in the changes instead of atoms

Participant #08 demonstrated a different application of the mapping strategy (Table 54). Participant #08 looked for changes in the molecules, charges and bonds forming or breaking, and described tracking the electrons used in the changes to determine how to draw the EPF arrows. Participant #08's strategy to track changes in reactants and products to determine how EPF arrows should be drawn is a simple strategy that experts use to obtain relevant information such as stereochemistry. By mapping the differences between reactants and products, reactive sites become clear and can be used as a starting point when learning how to draw EPF arrows. Although participant #08 had a solid plan, they drew incorrect EPF arrows. Thus, it is unclear whether tracking specific electrons used in the changes of the reaction without mapping atoms and electrons is beneficial.

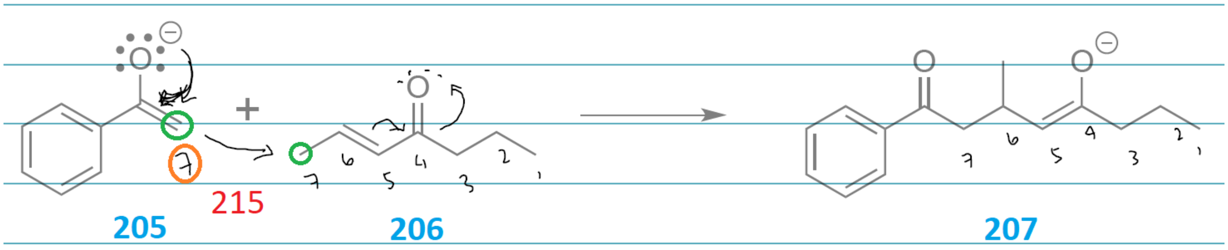
Table 54. Participant #08 described mapping changes in electron movement instead of atoms. The participant's markings are in black.

Question 3	
	
Int:	"*How do you decide where to draw your arrows, so where it starts from and where it ends at*"
#08:	*"The arrows, here I think. We always have to look for like a change, movement of electrons (…) so either a pi system or a breaking or making of a bond which are the only real changes of electrons we have so when we have that, the creation of a charge would be another one. Whenever we have something like that, it could change in the structure. We know the electrons have moved somewhere, so we have to draw an arrow to show where they have moved."*
Int:	*"Okay, so where the arrow ends, is where the electrons ended?"*
#08:	*"So whatever becomes more negative is wh"ere we have the point of the arrow, like that's where the electrons have moved. And so like really the whole point I guess of this is looking for where something has been neutral becomes positive on one side and negative on the other and by looking at that we know not only do we have to draw an arrow, but which direction we have to draw it."*

Section 3.32: Emphasis on mapping carbon atoms

Mapping carbon atoms was a common theme amongst participants. Similar to participant #01, participant #11 focused on mapping carbon atoms throughout the interview without mapping other atoms or electrons (except for one oxygen atom in question 3). Participant #11 mapped the carbon atoms of molecules 206 and 207 numerically while working on question 2 (Table 55). When asked about their labels, participant #11 described their labels as the positioning of each carbon atom, demonstrating they were tracking specific carbon atoms in the reaction. Although participant #11 emphasized the carbon atoms, participant #11 described a connection being made on the 7th carbon atom of molecule 206 (Table 55), noted by the “7” circled in orange (Table 55). The location of bond formation is incorrect as the bond should be formed on the 6th carbon atom. Participant #11 demonstrated they did not see the methylene carbon (Table 55 circled in green on molecule 205), as the products were incorrectly labelled (Table 55 molecule 207). Although the mapping emphasis was on the carbon atoms, participant #11 incorrectly labelled the carbon atoms.

Table 55. Participant #11 incorrect mapping for question 2. The participants’ markings are in black. The researcher’s labels in red indicate EPF arrows. The researcher’s labels in blue indicate molecular species. The researcher’s circles in green indicate the methylene and methyl groups.

Question 2 – Incorrect Mapping	
	
Int:	*“What does the labeling tell you?”*
#11:	*“Oh the carbons? […] Um, the position of the car…, into each individual carbon.”*
Int:	*“What did you label that one right there?”*
#11:	*“Oh seven ‘cause that’s kind of where it connects right now.”*
Int:	*“**What about the other seven you have**? [circled in orange]”*
#11:	***“That’s just saying this is where it connects.”***
Int:	“Would that help you being able to draw the arrow?”
#11:	“Well at this point I would just say this [Arrow 215].”

Section 3.33: Summary

This section reviewed all participants’ mapping strategies (n = 4). A successful mapping strategy observed included conserving carbon atoms and reflecting on their labels to determine the reactive sites correctly. When I observed mapping, the labels were generally on the carbon atoms. I observed several types of errors in the data attributed to surface features. When participants mapped the implicit carbon atoms, they did not map the methylene group in the products. Participants who mapped used numerals to identify the carbon atoms, but most participants could not differentiate surface features in the reactants and products. One participant demonstrated how they obtained the correct bond location through their mapping strategy, demonstrating the effectiveness of the mapping strategy.

Section 3.34: Charges

To review charges, please see Section 1.10: Charges as symbols. I looked at participants' use of charges as a symbol in this section guided by research question 2.

Section 3.35: Charge definitions

Every participant gave reasonable definitions for both negative and positive ions. For example, participant #01 described that a negative charge indicates an extra electron (Table 56). Similarly, participant #04 described learning in a lecture that a negative charge indicates that the atom has extra electrons or bonds which can be donated (Table 56), while a positive charge indicates the atom will gain electrons (Table 57). Other participants similarly described a positive charge as missing electrons. For example, participants #07 and #12 described a positive charge lacking electrons (Table 57). Every participant held a similar definition for positive and negative charges, where the charge is due to the atom either gaining or losing electrons, with all participant examples in Appendix 24. Participants' discussions of losing or gaining electrons with respect to charges demonstrated a connection between charges and electron movement. For example, all participants described transplanting while working on question 4, where two charged species were made as a result of losing and gaining an electron. For example, participant #13 described the nitrogen atom gaining electrons resulting in the negative charge, and participant #03 described the carbon atom losing electrons resulting in the positive charge (Table 58).

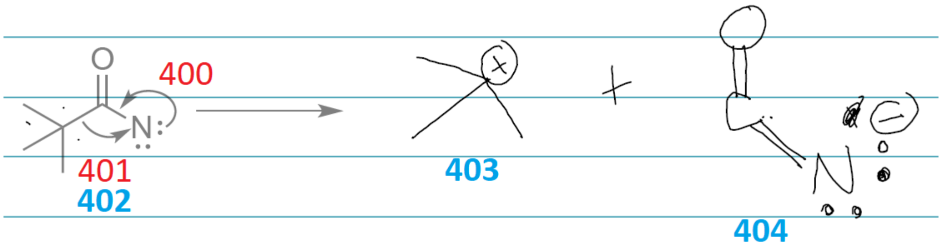
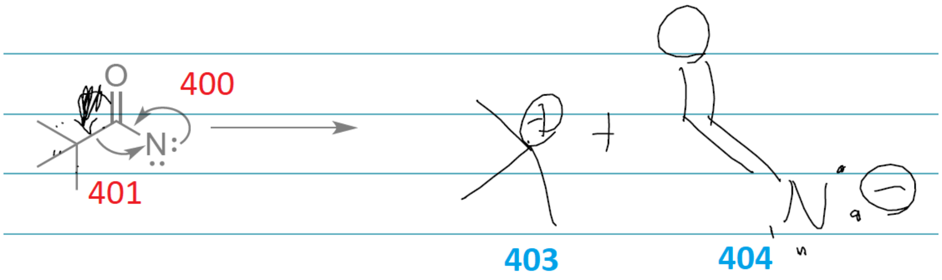
Table 56. Participants #01 and #04 definitions for negative charges.

Negative Charges	
Int:	*"How did do use charge to help you um solve this problem?"*
#01:	*"Because it has a minus charge it has it technically has one extra electron that it doesn't normally have."*
#04:	*"Okay well we learned in class at least that negative charges mean that it must've uh gained, or has more lone pairs or more bonds or something […] so if it has a negative charge that means it must have more bonds or more um uh lone pairs, which means it has electrons to donate […] To other species."*

Table 57. Participants #04, #07 and #12 definitions for positive charges.

Positive Charges	
#04:	*"If there's a positive charge it means it must have less, which is why that equation would create a positive charge on it so it can receive electrons instead."*
#07:	*"If you've lost a pair of electrons it becomes a plus charge—positive charge."*
#12:	*"There's a positive charge on this carbon, which means it's missing an electron."*

Table 58. Participants #13 and #03 reasoned the negative and positive charges by gaining or losing electrons. The participant's markings are in black. The researcher's labels in red indicate EPF arrows. The researcher's labels in blue indicate molecular species.

Question 4	
	
#13:	*"This nitrogen [Molecule 404] is still gonna have two lone pairs however, so originally it have a lone pair to this bond […] And then it got a pair of electrons from this bond so that's gonna give it a negative charge [Molecule 404] […] And this carbon here though only has three bonds so I'm gonna give it a positive charge [Molecule 403]."*
Question 4	
	
#03:	*"This carbon. Would have a positive charge [Molecule 403]. […] because before it had four things Four bonds to it, so looking at the formal charge, four minus four is zero making it neutral, but since we broke the bond and gave it to the nitrogen, it has a positive charge [Molecule 404], because it only has three bonds attached to it."*

Section 3.36: Students saw charges as important

Nine out of twelve participants described charges are important factors when solving organic chemistry reactions. The interviewer asked nine participants how important charges are when solving the questions, and they responded that charges are important. For example, participant #11 described that charges were pretty important, and participant #06 described "charge was everything" (Table 59). The other eight participants describing charges as important are in Appendix 25. Two participants relied on charges and emphasized that charges were necessary. For example, participant #06 described having difficulty thinking outside of charges, while participant #08 relied on charges as a marker for reactivity (Table 59). The last three participants did not describe charges as important and were not prompted by the interviewer. The three participants who did not describe charges as important might have held the same interpretation that charges are important since the nine participants only described charges as being important when prompted (Appendix 25).

Table 59. Participant #11 described charges are important, and participants #06 and #08 described a reliance on charges.

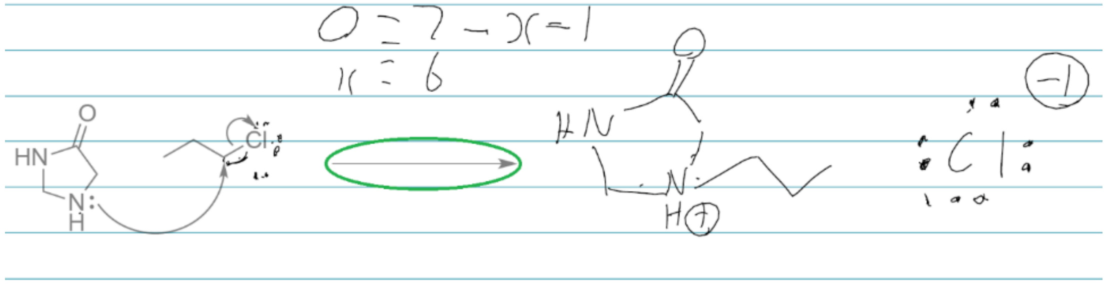
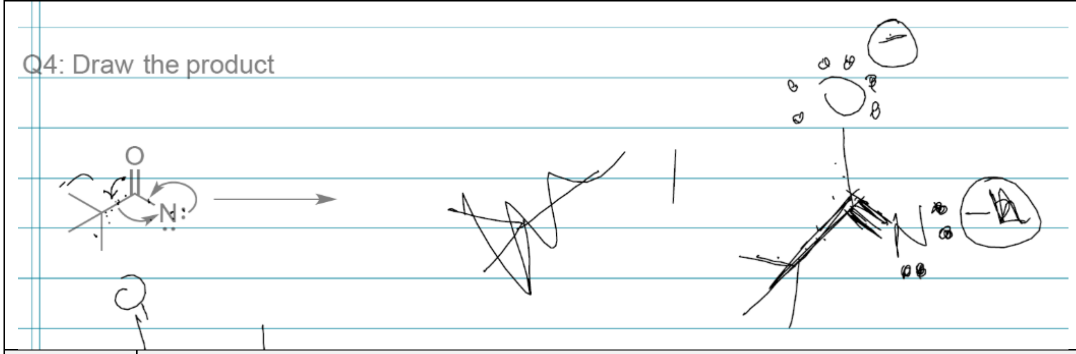
Charges are seen as important	
Int:	*“How important is charge to you when you are deciphering what’s going on in a mechanism like this?”*
#11:	*“Yeah, so I would say pretty Important.”*
Emphasis on charges	
#06	*“Charge was everything, […] I think I might’ve had to think of it outside of charge and I’m pretty bad at that.”*
#08:	*“I find kind of like rely on charge, like cause if there’s no charge you’re not really doing anything […] so charge is very important.”*

Section 3.37: Participants used charges as a cue to problem-solve

Participants used the positive and negative symbols to solve reactions and as instant feedback on determining whether their answers were correct. For example, participant #12 described charges as something that needed to be balanced throughout, and if there was an extra or missing charge, participant #12 determined they made a mistake (Table 60). When multiple charges were present, participants became hesitant in their answers. For example, participant #03 described the product as having more charges than the reactants and concluded the reaction arrow should be pointed in the opposite direction (Table 60 reaction arrow). Similarly, participant #05 described their product had too many charges and determined something was incorrect (Table 60). Participants used the positive and negative symbols as a cue to check their answers for errors.

Table 60. Participants #12, #03, and #05 used charges to check if their answer was correct. The participant’s markings are in black. The researcher circled the reaction arrow in green.

Balancing charges	
#12:	*“The charges need to be balanced, I always check the charges to make sure because um I know I’ve made a mistake if I have like two um positive charges on one side and then a positive and a negative on the other because then something doesn’t add up and I have to recheck everything and find my mistake because it should be balanced.”*

Multiple charges are interpreted as incorrect	
	
#03:	*"When it comes to formal charges, they want to become neutral. So they want to stay neutral right. But they here they are natural, and then they are losing their formal charges […] yeah it would make more sense for the arrow going the other way (reaction arrow)."*
	
#05:	*"So it's just negative, so this is two, <u>this</u> is a negative, that's a negative […] Um it tells me that it might not be right because you usually want something with like the least amount of charges."*

Section 3.38: Negative and positive charges indicate reactive sites

Participants used charges as a piece of information connected to reactivity. For example, participants #05 and #13 correctly described charges as a reactive site (Table 61). Additionally, participant #07 included charges when problem-solving, while participant #09 used charges to provide information regarding electron movement (Table 61). Charges were also important to participants when breaking and forming bonds. For example, participants #08 and #03 described using charges and electrons to break and make bonds (Table 62). In addition, two participants viewed charged species as incomplete. For example, participant #13 described charged species required an additional step (Table 63). Similarly, participant 06 described the two charged structures as intermediates rather than a final product (Table 63). Participants used charges to describe reactivity, locations where bonds will form or break, and interpreted charged species as incomplete.

Table 61. Participants #05, #13, #07, and #09 described charges as a reactive site.

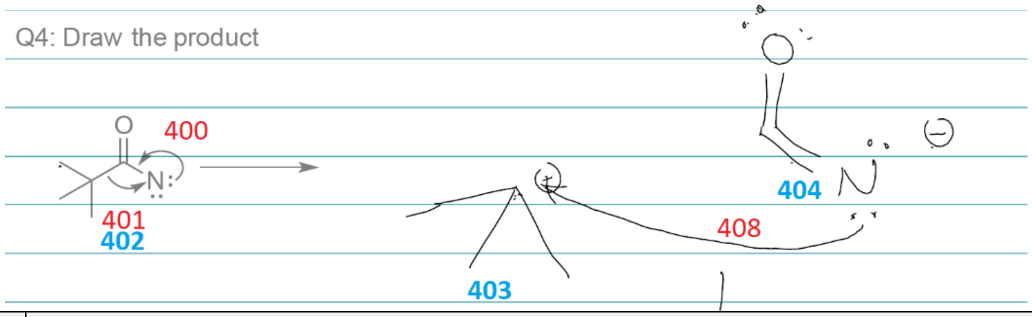
Reactivity

#05:	*“I guess if it’s like missing, so if it’s positive […] Then I guess it would be missing either like a bond or like a pair of electrons or something […] so I guess it kind of shows you that something’s happening there.”*
#13:	*“It kinda helps predict what’s gonna happen because if you see a charge you kinda know something’s gonna happen to it.”*
#07:	*“You see the cha—charge it means—it shows that you’ve lost something or gained electrons of some sort, and then […] you know what reacted with what and it can help you continue your problem solving thinking.”*
#09:	*“The first thing that I look at, like boom there’s a charge there it’s like a hey like a little red flag […] kinda thing, not red flag but similar to that where um I’m drawn to that immediately and it’s kind of easier to see maybe what would move, like the electrons are what, where charges can be without having to do anything.”*

Table 62. Participants #08 and #03 associated bond-forming and breaking processes with charges.

Bond-breaking and forming processes	
#08:	*“The charge is like pretty important I guess, cause like the whole idea of what’s going on, and like breaking bonds and making bonds is the electrons and so the electrons like influence the charge.”*
#03:	***“***To attach things together you have to use the charges and the lone pair of electrons to be able to give and receive electrons and make and form bonds.”*

Table 63. Participants #13 and #06 described the reaction as incomplete due to the charged species. The participant’s markings are in black. The researcher’s labels in red indicate EPF arrows. The researcher’s labels in blue indicate molecular species.

Charged species as incomplete	
#13:	*“If you did something and it made a charge you’re like okay well I’m not done though it’s probab- or not all the time, but sometimes* ***if there’s a charge on a place that there’s not normally a charge you can tell that another step is gonna happen to that area.”***
Question 4	
	
#06:	*“There’s um, like this is left positive [Molecule 403], this is left negative [Moleculec 404] and it makes it seem much more like an intermediate […] Than a final product.”*

Section 3.39: Participants’ ideas regarding neutralization of positive and negative charges

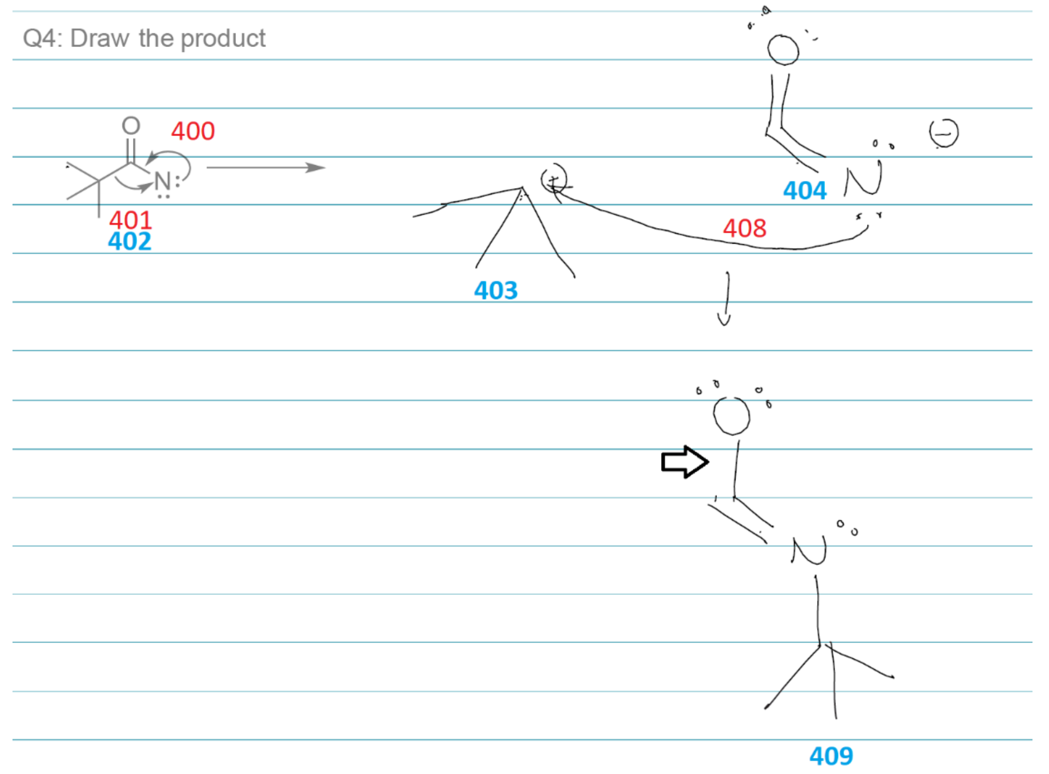
Participants revealed charges as something that required neutralization. For example, participant #03 described that formal charges want to become neutral, where a positive charge accepts electrons to become neutral, and a negative charge gives electrons to become neutral (Table 64). Participants also tried to put the opposing charges together to cancel them out. For example, participant #01 described putting a negative and positive together would make a neutral compound (Table 64). Participant #06 previously mentioned that the electrons moved from negative to positive and applied the concept to question 4 (Table 65). Participant #06 brought the negatively charged nitrogen to the positively charged carbon, effectively neutralizing the two charged species. Participant #06’s final structure had one error showing a carbon-oxygen singular bond that should be a double bond (Table 65 molecule 409). While working on question 5, participant #06 repeated the negative to positive by drawing an extra EPF from the negatively charged chlorine atom pointing to the positively charged nitrogen atom, resulting in the impossible pentavalent nitrogen (Table 65). Participants saw charges as reactive, a reactive site, and something to neutralize. Participants described charges could either give or receive electrons to neutralize, or the positive and negative charges brought together would neutralize them.

Table 64. Participants #03 and #01 described neutralizing charges.

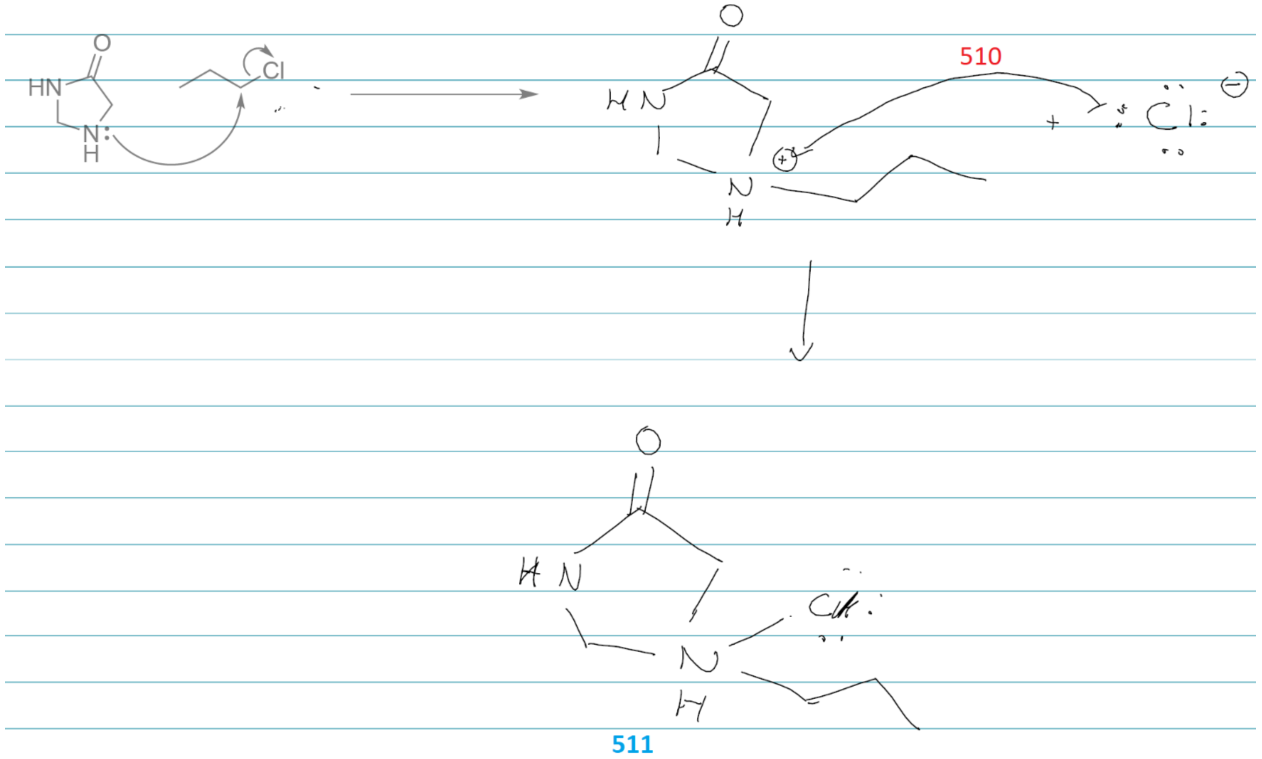
Neutralization	
#03:	*“To attach things together you have to use the charges and the lone pair of electrons to be able to give and receive electrons and make and form bonds. **So when that has a positive charge, it wants to grab electrons to make it’s charge neutral. And something that has a negative charge wants to give it’s electrons so it can become neutral as well. Cause all atoms are happy when they are neutral.**”*
#01:	*“So in a neutral compound there’s a positive and negative putting them together would make no charge.”*

Table 65. Participant #06 described electrons moving from negative to positive. The participants’ markings are in black. The researcher’s labels in red indicate EPF arrows. The researcher’s labels in blue indicate molecular species. The researcher’s black arrow indicates the carbon-oxygen bond, which should be a double bond.

Electrons moving from negative to positive	
#06:	*“’Cause **it’s all just movin- moving electrons** … **That’s what the arrows show**, it’s just moving electrons around, so uh it’s all about **how the electrons want to move, so really basically just negative to positive**.”*
Question 4	



#06:	*“How I interpreted this, this seems like an intermediate, so what I think from what I found,* ***what should happen is this nitrogen*** *[Molecule 404]* ***bonds with that*** *[Molecule 404] and then it’s, goes to become uh right double bonded into the nitrogen, the nitrogen has a single lone pair coming off of it, and then that’s bonded to the three methyl groups* ***Now it’s, this carbon’s happy, this oxygen’s happy, one, two, three, four, five, then the nitrogen’s neutral, this carbon has the four bonds so it's happy and it seems like that should be the final product*** *[Molecule 409].”*
Question 5	



#06:	*“**Because this chlorine is negative here, this nitrogen is positive, they’re not entirely happy with their charges** […] **they want to uh balance their charges I suppose** […] **They want to be neutral** […] And this uh this ele- this lone pair forming a bond with the nitrogen [Arrow 510] is the only way I can see that they can uh become neutral.”*

Section 3.40: Summary

Participants interpreted charges as symbols by pulling relevant information from their long-term memory. Participants used charges as instant feedback to determine if their answers were correct. If the structures contained too many charges, the answers were interpreted as incorrect by reasoning that the structures should have the least number of charges. Participants viewed charges as something that needed balancing throughout the reaction. The participants knew something was incorrect if there was an imbalance of charges, demonstrating that participants used the charges as representations for problem-solving.

Participants also attributed charges to several factors: reactivity, electron movement, bond-forming processes, and bond-breaking processes demonstrating participants do find positive and negative charges as meaningful representations. Participants described neutralizing both negative and positive charges in different ways. A positive charge needs an electron to become neutral. A negative charge needs to give an electron to become neutral. Lastly, A negative and positive charge brought together would neutralize both charges.

Chapter 4: Discussion

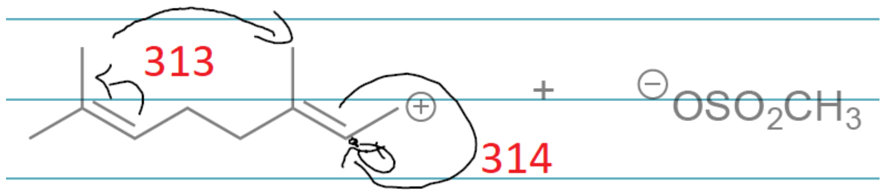
In this work I explored how undergraduate organic chemistry students interpret and understand organic chemistry representations. Twelve Organic Chemistry I students participated in qualitative interviews that were designed to explore their initial interpretations of the EPF. We viewed the data through the lens of the chemistry triplet to determine how the participants understood the EPF arrows as symbols and their submicroscopic processes. We also viewed the data through modern IPT to determine what knowledge of the organic chemistry symbols and information participants were pulling from their long-term memory, accessed via their working memory.

Guided by the chemistry triplet, we found that all the participants in the study described the EPF arrows as a depiction of electron movement (symbolic representation), including whether the EPF arrow illustrated a bond-breaking or forming submicroscopic process (Table 66). Participants connecting the EPF arrows to submicroscopic processes are consistent with the previous interview studies (Galloway *et al.*, 2017; Bongers *et al.*, 2020), reinforcing the notion that organic chemistry students following the new curriculum at the University of Ottawa attribute meaning to the EPF (Flynn and Ogilvie, 2015). The consistent connection between the symbolic and submicroscopic levels between studies demonstrates students are finding meaning in the EPF arrows under the new curriculum and supports the practicality of dedicating the first reactivity section of the course to mastering the EPF arrows (Flynn and Ogilvie, 2015).

The findings are different from studies at other institutions that described students finding the EPF arrows as meaningless representations (Bhattacharyya and Bodner, 2005; Anderson and Bodner, 2008; Ferguson and Bodner, 2008; Kraft *et al.*, 2010; Grove, Cooper, and Rush, 2012). Students ,found the EPF arrows to be a meaningless mental exercise (Ferguson and Bodner, 2008), memorized the EPF arrows for a previous reaction and decorated the task with EPF arrows (Bhattacharyya and Bodner, 2005; Grove, Cooper, and Rush, 2012; Graulich, 2015), or proposed the EPF arrows after determining the product (Grove, Cooper, and Rush, 2012). The findings support the claim that representations act as barriers to a deeper understanding (Ferk *et al.*, 2003; Kozma and Gilbert, 2005; Gilbert and Treagust, 2009), with the EPF arrows acting as a barrier to a deeper understanding of organic chemistry (Grove, Cooper, and Cox, 2012).

Table 66. EPF arrow interpretation as electron-movement, bond-breaking, or bond-forming processes.

Electron-Movement
"*I interpreted like the movement of electrons in particular from the arrows*."



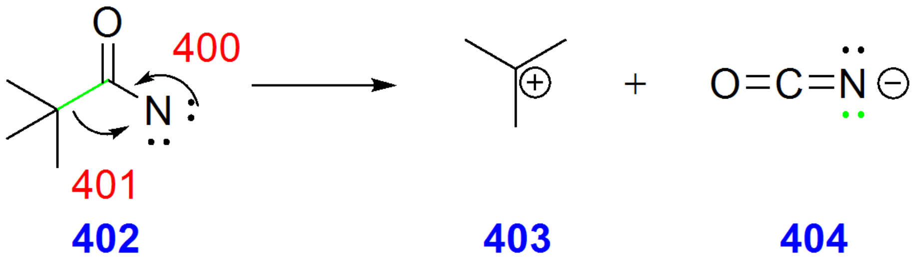
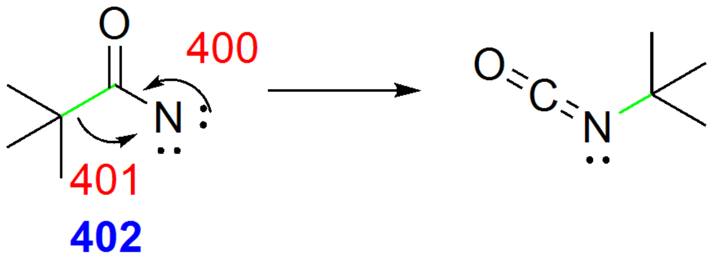
Instruction: EPF arrows must be drawn from electrons and point to an atom or bond

Bond-breaking and bond-forming processes

"*Because when something [Arrow 502] is pointing from a bond to an atom, the bond is breaking. So like things point from electrons to an atom [Arrow 501], the bond is being formed.*"

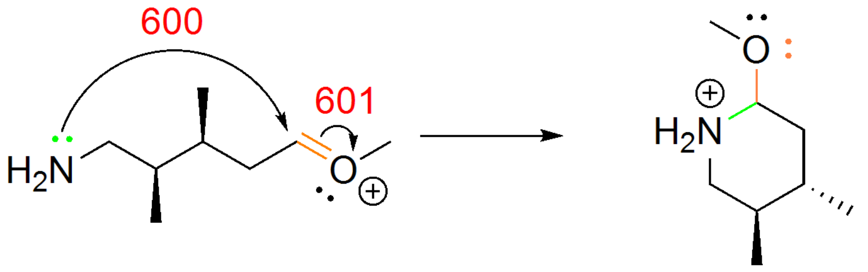
Aligned with modern information processing theory, we found participants retrieved relevant knowledge from their long-term memory to assist in the interview tasks. Participants retrieved relevant information from their long-term memory as an interpretation of the EPF arrows discussed through their working memory. The participants in this study could correctly determine bond-breaking EPF arrows but found it challenging when an EPF arrow showed both a bond-forming and breaking process. The participants' interpretations were correct when describing an EPF arrow pointing from a bond-to-an atom as bond-breaking and an EPF arrow pointing from an electron source to an atom as bond-forming. Participants correctly identified the bond-breaking EPF arrows, and although having the correct interpretation, participants found identifying the bond-forming EPF arrows on intramolecular reactions challenging because participants transplanted the electrons instead of forming a bond. Some participants associated atom movement with the EPF arrows and are not entirely inaccurate as atom movement also occurs. However, the purpose of the EPF arrows is strictly for electron movement. The drawn EPF arrows generally started from an electron source but pointed to an incorrect location. Starting the EPF arrow from an electron source demonstrated participants retrieved information from their long-term memory and understood they needed an electron pair to move. The arrowhead is where participants had trouble as the EPF arrows generally pointed to an incorrect location. The difficulty of the questions may have played a role because only one participant was successful in question 3. Participants have recently started their organic chemistry careers and demonstrated the EPF arrows are meaningful through interpretation of the EPF arrows. Every participant implicitly used the bond-to-atom interpretation as every participant described a similar transplanting electron process for question 4, the Curtius rearrangement (Appendix 2). All participants might have held the same idea that no bonds were forming, as all of the drawn structures did not contain any bonds formed and only transplanted electrons. Using participants' previous discussions of interpreting bond-breaking EPF arrows and not considering bond formation put together could explain why participants transplanted electrons. Transplanting electrons demonstrates an incorrect interpretation, retrieval of incorrect prior knowledge or inability to retrieve relevant knowledge from the long-term memory, of the EPF arrows because the submicroscopic process is interpreted as electrons moving when it should be a bond-forming. Question 4 was also previously used in an interview study which found the same transplanting process with the same drawn structures (Galloway *et al.*, 2017), suggesting a common misinterpretation of the EPF arrow. The common misconception was that an EPF arrow was interpreted as transplanting electrons instead of a bond-forming process (Table 67). The previous transplanting theory was that students found it challenging to keep the electrons on the originating atom (Galloway *et al.*, 2017). The transplanting electrons error may be similar to a previously reported study where one student called themselves "electron goddess" but differed as the student moved electrons to wherever they wanted (Ferguson and Bodner, 2008), while participants in this study moved the electrons to where the arrow pointed.

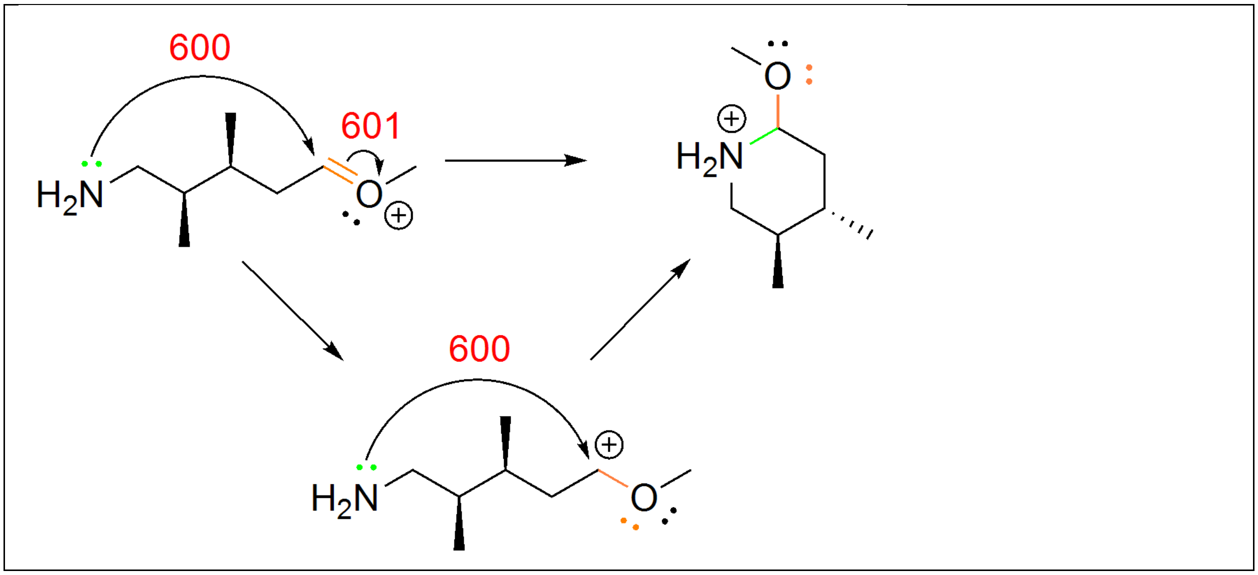
Table 67. Transplanted response and expected bond-forming answer for the Curtius rearrangement.

Transplanted Response

Expected Answer


Most participants in this study interpreted the EPF arrows stepwise as a problem-solving approach while visualizing the EPF arrows as concerted or stepwise (correct and incorrect, respectively). The stepwise interpretation was first reported in the previous interview study, where students discussed a reaction occurring one EPF arrow at a time (Galloway *et al.*, 2017). That interview study could not differentiate whether students interpreted or visualized the EPF arrows occurring stepwise. The present study aimed to see how students visualize and approach the EPF arrows. When multiple EPF arrows were present, the participants described a stepwise problem-solving approach and visualized the reaction in either a concerted or stepwise manner. Participants described their problem-solving approach by interpreting each EPF arrow one at a time, stepwise. Participants described the stepwise interpretation made understanding how the reaction proceeded easier. Participants drew unlikely resonance structures as they interpreted each EPF arrow stepwise, and used the structures to provide meaning for the next EPF arrow (Table 68). The creation of the unlikely resonance structures demonstrated participants understood the EPF arrows depicted electron movement as a representation. All stepwise findings are similar to the previous interview study (Galloway *et al.*, 2017). The previous theory of a stepwise interpretation was that students took a stepwise approach to reduce the amount of cognitive effort required to solve reactions (Galloway *et al.*, 2017). In addition to reducing the amount of cognitive effort, the findings suggest the stepwise interpretation of the EPF arrows is due to the ease of interpreting the EPF arrows one at a time with the cause-and-effect reasoning that provides each EPF arrow with a purpose. Prior studies found when students approached the EPF arrows logically and organized, they were more successful (Grove, Cooper, and Rush, 2012). Students described that animations helped visualize electron movement (Bongers *et al.*, 2020). Alternatively, prior studies suggest that students do not interpret the EPF arrows but memorized EPF arrows for a previously learned reaction and decorated the task with EPF arrows (Bhattacharyya and Bodner, 2005; Graulich, 2015). Students gave the EPF arrows after determining the product demonstrated the EPF arrows were meaningless for those students (Grove, Cooper, and Rush, 2012). The EPF arrows are a tool chemists use to represent and understand how a reaction occurs. Understanding how a reaction occurs is essential in chemistry. Educators should emphasize to students that EPF arrows occur concertedly within a given mechanistic step taught through practice problems to gain mastery, assessed through assignments or examinations. Participants described interpreting the EPF arrows in a stepwise manner is easier to interpret than all at once, and approached the EPF arrows stepwise as a method of understanding how a reaction occurred while some participants retained the understanding the EPF arrows occur concertedly.

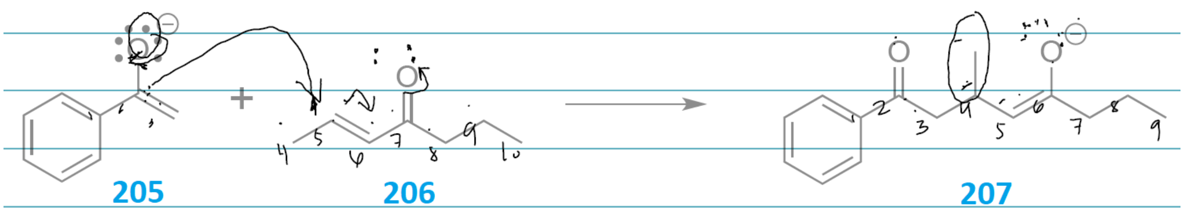
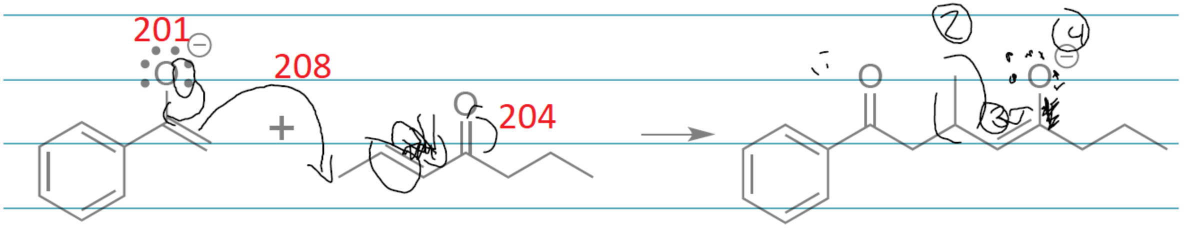
Table 68. Concerted and stepwise interpretation of the EPF arrows.

Correct concerted interpretation **EPF arrows 601 and 602 occur as a simultaneous bond-forming and breaking process**

Incorrect stepwise interpretation **Interpreting the EPF arrows one at a time resulting in an unlikely intermediate structure**



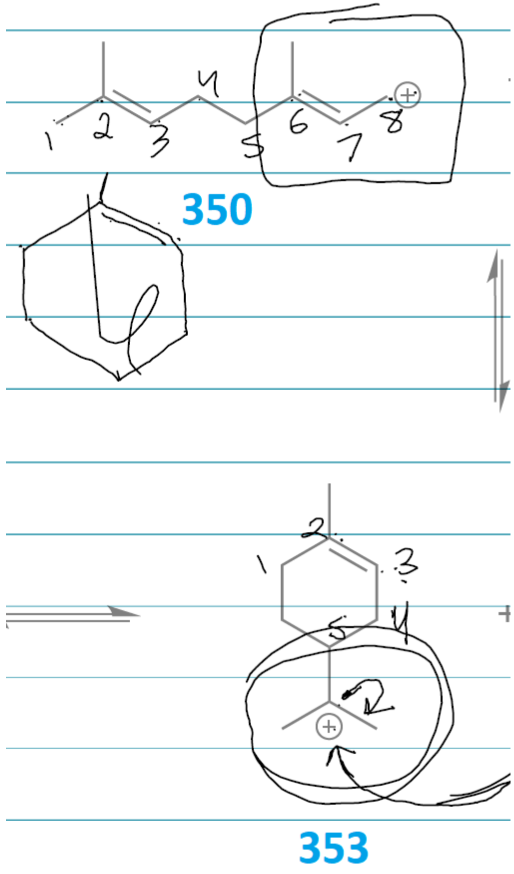
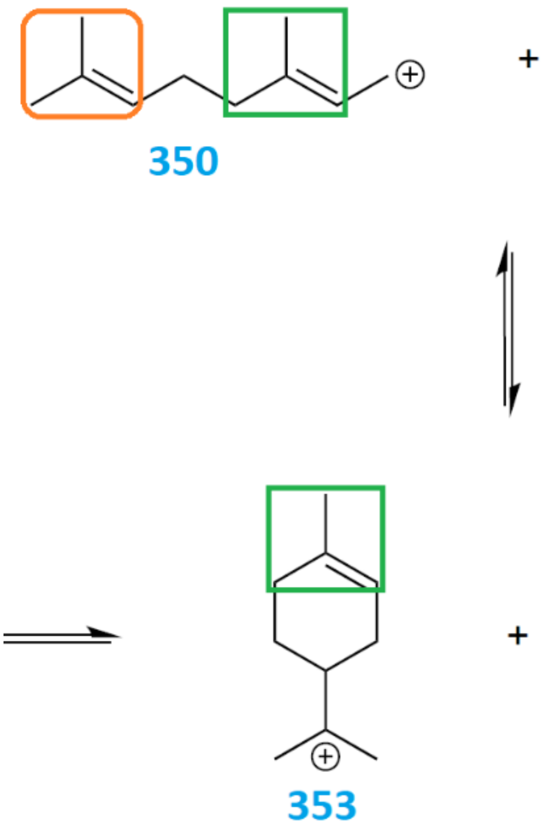
The participants in this study generally approached the interview tasks in the same way. Participants' initial strategy for solving questions was to compare reactants to products via surface features being charges, bonds, electrons, or the number of molecules. Participants could accurately determine which surface features were relevant but faced difficulty when it came to drawing EPF arrows (Table 69). Most participants drew EPF arrows starting from an electron source, demonstrating the participants understood that the EPF arrows require a pair of electrons. The challenge came when participants drew the arrowhead as most EPF arrows pointed to an illogical position. In the current study, participants faced difficulty when drawing and interpreting bond-forming EPF arrows on the intramolecular Curtius rearrangement. The intramolecular Curtius rearrangement (Question 4 of the interview, Appendix 2) contains an EPF arrow illustrating a bond-forming and breaking process that participants interpreted as bond-breaking and transplanted the electron pair. Participants' interpretations were an EPF arrow pointing from an electron to an atom is bond-forming, and an EPF arrow pointing from a bond-to-atom is bond-breaking (Table 66). Previous studies reported interpretations made in organic chemistry such as (1) for protonated epoxides, the group will add onto the carbon facing in the opposite direction of the hydrogen atom (Bongers *et al.*, 2020), (2) tertiary alkyl halides react via S_N1 while primary alkyl halides react via S_N2 (Bodé *et al.*, 2019), (3) a nucleophile always attacks a positive charge (Kraft *et al.*, 2010), or (4) enols are reactive at the α-carbon (Caspari, Kranz, *et al.*, 2018). However, interpretations of EPF arrows have not been reported. The previous interview study used the Curtius rearrangement and found the same drawn structures as participants in this study (Galloway *et al.*, 2017), suggesting participants faced difficulty with the Curtius rearrangement, where possible factors include intramolecular rearrangements or explicit and implicit atoms. The common misinterpretation of the EPF arrows for the Curtius rearrangement between studies demonstrates participants are interpreting the EPF arrows as a representation and need further clarity on how to interpret the EPF arrows.

Table 69. Participants #01 and #07 compared the products and reactants to determine how to draw the EPF arrows. Participant #01 provided plausible EPF arrows, while participant #07 incorrectly drew EPF arrow 208 along with six other participants.

Question 2	
	
#01:	*"I was looking at the products so it was easier to know how the bonds were going to move um to form the compound."*
Question 2	
	
Int:	*"Thanks, um, tell me um, how did you identify uh, how to draw those arrows?"*
#07:	*"I looked at the product—product side […] to see what changed from the two original reactants and then processed going backwards."*

Participants faced difficulties when comparing implicit atoms as a surface feature. Question 3, step 2 of 3 (Appendix 2), highlights participants' challenges with implicit atoms as the step consisted of only implicit atoms. Participants incorrectly assumed the first alkene in the reactant was the same in the product (Table 70), consistent with the previous interview study (Galloway *et al.*, 2017). The previous theory with implicit information was that students could not extract relevant information from the structures resulting in a barrier to further chemistry education (Cooper *et al.*, 2012). The findings suggest the participants faced difficulty extracting relevant information from the implicit atoms. Participants missed an important methyl group suggesting the implicit atoms are "lines" that hold no physical meaning (Treagust *et al.*, 2003; Anderson and Bodner, 2008).

Table 70. Participant #09 assumed the first alkene in the reactant was the first alkene in the product. The correct alkene is in the green box on the reactant and product.

Participant #09	Correct alkene is boxed in green.
	

The previous exam analysis found minimal incorrect, reversed, or extra EPF arrows (Flynn and Featherstone, 2017), while some participants in this study faced difficulty drawing the arrowhead (Figure 15). The differing results may be due to the time of data collection. Students in the exam study had more experience than the participants because the participants had recently learned about the EPF. Comparing the data, participants in this study had the least amount of knowledge than students in an exam analysis (Flynn and Featherstone, 2017), who had a substantial amount, which suggests students find meaning in the EPF arrows somewhere between being taught the EPF arrows and the exam. However, students finding meaning in the EPF arrows somewhere along the course only applies if the course was conducted in the same manner.

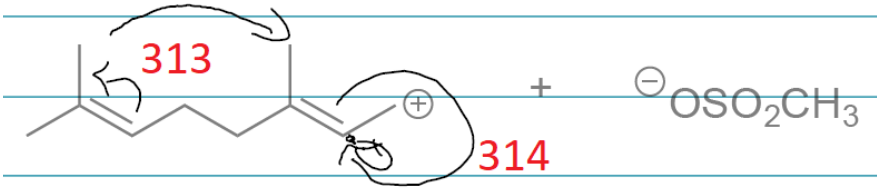


Figure 15. Some participants faced difficulty drawing the arrowhead as the arrowheads did not point to an appropriate position.

There was minimal physical evidence of mapping in the data, although the mapping strategy is associated with higher success rates (Bodé and Flynn, 2016). All participants verbally mapped the structures via numerals, but most were not physically labelled on paper, meaning participants' verbal mapping could not be coordinated onto any structure post-interview. Participants' verbal counting could be interpreted in either direction, left to right or right to left, and could also be mistaken for electrons or bonds, making verbal counting unreliable when determining if participants applied the mapping strategy. The symbols used to map each molecule do not appear meaningful to some participants as there was minimal physical evidence of the mapping strategy. Since participants have only recently learned about the mapping strategy, it is possible that some participants could not pull relevant information from their long-term memory or did not see the value in the physical labels as a representation. Similarly, the lack of mapping in the exam analysis might be due to a verbal or mental mapping of the molecules without explicit physical labels (Flynn and Featherstone, 2017). When mapping was observed, the labels were mainly on the carbon atoms (Table 70), similar to the previous studies (Bodé and Flynn, 2016; Galloway *et al.*, 2017). A participant demonstrated the mapping strategy's effectiveness as they solved the question by determining the correct bond location through the assigned labels. It is unclear whether participants found the mapping strategy meaningful as there was minimal physical evidence and if participants faced difficulty with the mapping strategy or EPF arrows.

Participants described charges as an important factor when solving reactions. When prompted, participants described charges as an important feature, suggesting that all participants thought the charges were important and did not state them. Similarly, students only described Lewis acid and base theory when asked (Cartrette and Mayo, 2011). Participants in this study relied on charges as an explicit representation to determine how the reaction proceeded, where the reaction would occur, and as a problem-solving tool. Participants depending on charges is consistent with previous studies regarding reactivity (Galloway *et al.*, 2017; Carle *et al.*, 2020), problem-solving (Galloway *et al.*, 2017; Carle *et al.*, 2020), acid-base chemistry (Cartrette and

Mayo, 2011; Anzovino and Bretz, 2016), nucleophiles, and electrophiles (Anzovino and Bretz, 2015). Participants interpreted charges as a representation of their long-term memory and associated multiple chemistry concepts, demonstrating charges are representations participants find meaningful. Participants used the number of charges as instant feedback to determine how the reaction proceeded. Some participants knew their answer was incorrect if the reaction contained too many charges (Table 71), similar to how an expert determines if their answer is correct. In addition, the participants gave correct IUPAC definitions of negative and positive ions (McNaught and Wilkinson, 1988), balanced charges throughout the reaction, associated bond-forming and breaking processes with EPF arrows, and described how to neutralize charges. Participants neutralizing charges are consistent with the previous interview study (Galloway *et al.*, 2017).

Table 71. Participant #12 described charges need to be balanced and understood a mistake has occurred if charges do not balance.

Balancing charges	
#12:	*"The charges need to be balanced,* *[…] I know I've made a mistake if I have like two um positive charges on one side and then a positive and a negative on the other."*

In this work, I aimed to explore students' initial interpretations of the EPF and found that students are thinking about how to interpret and draw the EPF arrows based on their knowledge, demonstrating that students find the EPF arrows meaningful. Even though participants had minimal experience with the EPF arrows, they established a solid understanding that the EPF arrows illustrate electron movement and bond-forming or breaking processes. Participants demonstrated that electrons are required at the arrow tail because the majority of EPF arrows started at an appropriate electron source. Participants also interpreted the EPF arrows, demonstrated by the concerted interpretation, stepwise interpretation, and transplanting process. While most studies report students do not find meaning in the EPF arrows because students provided EPF arrows after determining what the product looked like (Grove, Cooper, and Rush, 2012), students proposed illogical EPF arrows (Zotos *et al.*, 2021), students memorized the EPF arrows or previously learned EPF arrows for a reaction (Bhattacharyya and Bodner, 2005; Graulich, 2015), or students thought EPF arrows were an academic exercise (Ferguson and Bodner, 2008), similar to a "plug-and-chug" (Bhattacharyya, 2014). Combined with the previous work by the Flynn research group, the exam analysis found minimal errors with the EPF arrows and minor pentavalent atoms (Table 72)(Flynn and Featherstone, 2017), the first interview study found participants connected electron-movement to mapping, charges, stepwise and chemistry reasoning (Galloway *et al.*, 2017), and the current study demonstrated participants interpreted the EPF arrows (Table 73), it seems like the patterns of mechanisms curriculum at the University of Ottawa may contribute to students finding the EPF arrows meaningful, as students are thinking about how to draw the EPF arrows on reactions that are new to them. A possible harm is that students might interpret the EPF arrows as a singular process, leading to the transplanting electrons error.

Table 72. Previous exam and interview study by the Flynn Research Group demonstrating students

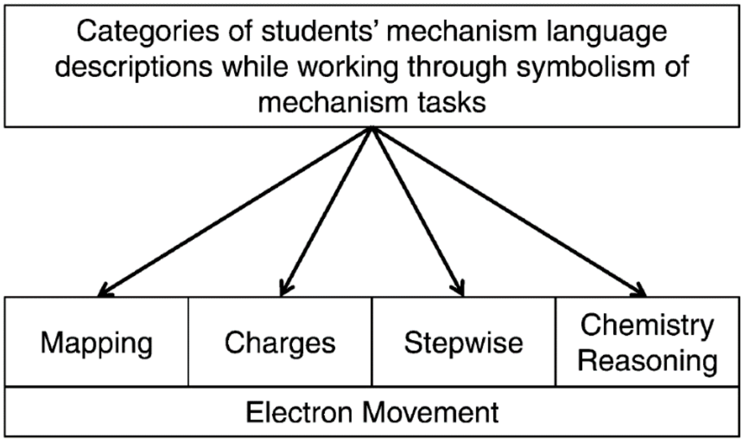
Exam analysis (Flynn and Featherstone, 2017)	**First interview analysis** (Galloway *et al.*, 2017)
Few reversed or illogical arrows	
Minor pentavalent atoms (<3%)	

Table 73. Participants in this study demonstrated interpreting the EPF arrows.

Current study demonstrating participants interpreted the EPF arrows	
Stepwise interpretation	**Transplanting interpretation**
Visualized the reaction occurring concerted or stepwise	Determined an EPF arrow pointing from a bond-to-an atom as bond-breaking
Easier to interpret stepwise as a problem-solving approach	Correctly determined which bond breaks
Cause and effect reasoning gives each EPF arrow purpose	Moved the electrons to where the EPF arrow pointed

Chapter 5: Conclusions

The primary goal of this research was to explore what initial interpretations and meaning students place on the EPF arrows as a representation after being recently taught. Every participant understood the EPF arrows as a symbol illustrated electron movement, a submicroscopic process. Every participant explicitly described the arrows as electron movement and drew EPF arrows starting from an appropriate electron source. Participants followed the instructions in the lectures to interpret which EPF arrows represented a bond-breaking or forming process, demonstrating that participants thought about the EPF arrows as a representation at the submicroscopic level. The results suggest students following the new curriculum at the University of Ottawa find the EPF arrows meaningful as a representation because they retrieved relevant information from their long-term memory to solve or interpret organic chemistry symbols when recently taught.

Another focus of this thesis was to explore how students visualized different elements of an organic chemistry reaction (research question 2), summarized in Table 74. Participants connected the stepwise and transplanting to the EPF arrows and demonstrated using the mapping strategy and charges to help solve the reaction. Participants explicitly described interpreting the EPF arrows stepwise as it was easier to understand and visualize how reactions occurred because participants found purpose in each EPF arrow. Participants demonstrated their interpretation of the EPF arrows highlighted by the transplanting process. Participants followed the bond-to-atom interpretation and correctly determined that the bond would break but incorrectly placed the electrons onto another atom, transplanting instead of forming a bond. Although there were minimal observations of the mapping strategy, one participant used the strategy to determine how they would draw their EPF arrow and correctly solved the question, demonstrating the effectiveness of the mapping strategy. The participants generally mapped the carbon atoms with labels. Mapping the implicit carbon atoms came with challenges because participants faced difficulty correctly translating the reactant onto the product. Every participant demonstrated a basic understanding of positive and negative charges, describing charges as an important surface feature when asked by the interviewer. Participants thought charges were a reactive species that determined where a bond forms or breaks, including neutralization of charges. Participants used charges as a representation to determine whether a structure was correct and an explicit surface feature to solve problems. The results suggest that participants interpreted several elements of an organic chemistry reaction as a representation and made meaningful connections at the submicroscopic level after being recently taught.

Table 74. Significant findings of how participants interpreted the EPF and organic chemistry representations.

Stepwise	Transplanting	Mapping	Charges	
Visualized the reaction occurring concerted or stepwise	Determined an EPF arrow pointing from a bond-to-atom as bond-breaking	Demonstrated mapping is an effective strategy	Provided IUPAC definitions of positive and negative ions	Interpreted charges as important explicit surface features
Easier to interpret stepwise as a problem-solving approach	Correctly determined which bond breaks	Labels on carbon atoms	Giving an electron to a positive charge would neutralize the positive charge	Reactive as the location of reaction and bonds breaking or forming
Cause and effect reasoning gives each EPF arrow purpose	Moved the electrons to where the EPF arrow pointed	Challenges with implicit atoms	Taking an electron from a negative charge would neutralize the negative charge	Bringing both positive and negative charges together would neutralize both charges
			Using charges as instant feedback	
Interpreting the EPF arrows		**Problem-Solving Approach**		

Research at the University of Ottawa found positive results that students find the EPF arrows meaningful as a representation, with similar findings at an institution with a similar revised curriculum and differing findings at institutions adopting the functional group approach. The Flynn group found minor reversed illogical EPF arrows with minor pentavalent atoms on an exam analysis (Flynn and Featherstone, 2017). Participants described mapping, charges, stepwise, and chemistry reasoning when discussing electron movement in an interview study (Galloway *et al.*, 2017). Another interview study found higher success rates on both familiar and unfamiliar reaction mechanisms under the new course format, in addition participants used the EPF as an initial problem-solving strategy similar to how an expert would solve a reaction (Webber and Flynn, 2018). The findings from this work demonstrated participants interpreted the EPF arrows with minimal experience. Michigan State University adopted a new curriculum, Organic chemistry, life, the universe, and everything (OCLUE), to improve student learning and focuses on the EPF early to emphasize how and why electrons flow (Crandell *et al.*, 2018). The Cooper group found on exam analysis that students were more likely to use the EPF arrows and were more successful than their counterparts who did not use the EPF under the new curriculum (Houchlei *et al.*, 2021). Institutions using the functional group approach report that their students do not find the EPF meaningful. Some participants drew EPF arrows after determining the product (Grove, Cooper, and Rush, 2012), memorized the EPF arrows (Bhattacharyya and Bodner, 2005), or viewed the EPF as an academic exercise instead of a problem-solving tool (Ferguson and Bodner, 2008). The findings suggest that the time spent mastering the EPF arrows early is beneficial when learning organic chemistry.

Section 5.1: Implications for teaching and learning

Participants could accurately determine an EPF arrow illustrating a bond-breaking process but found the bond-forming EPF arrows challenging. Since the participants were at the start of their organic chemistry careers, misconceptions were not surprising. Misconception of the EPF arrows need to be addressed as misinterpreting the EPF arrows could lead to errors such as transplanting electrons. Students can also use the curriculum's textbook, Mechanistic Patterns (Ogilvie *et al.*, 2018), as an additional source for further clarity.

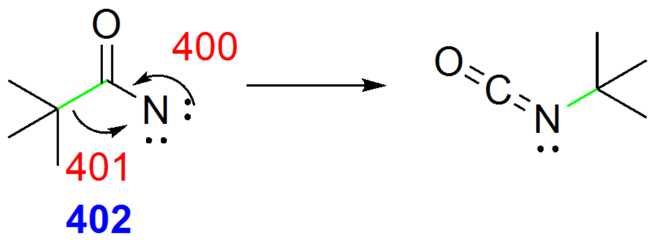
There are three key principles of the EPF (Table 75). When teaching, clarify how to interpret the EPF arrows with respect to the key principles. Educators can use chemical processes, such as bond-forming, bond-breaking, or transplanting electrons to demonstrate possibilities as products to determine the correct structure based off the key principles. Participants compared surface features between reactant and product as a strategy to determine how they would draw the EPF arrows. When participants face difficulty determining whether their structures are correct, they should compare the final structures between the processes. Table 76 illustrates two possible chemical processes for EPF arrow 401 as an interpretation, bond-forming and transplanting electrons. When learning, participants can compare the products between the bond-forming and transplanting process to determine that the bond-forming process is the more logical pathway due to following all three key principles (Table 75). The transplanting process does not follow principles two and three because charges were not conserved, and the electron pair did not stay with one of the bond's originating atoms. The transplanting process would be the non-logical pathway, while the bond-forming process is the logical pathway.

Table 75. Key principles of the EPF (Flynn *et al.*, 2016).

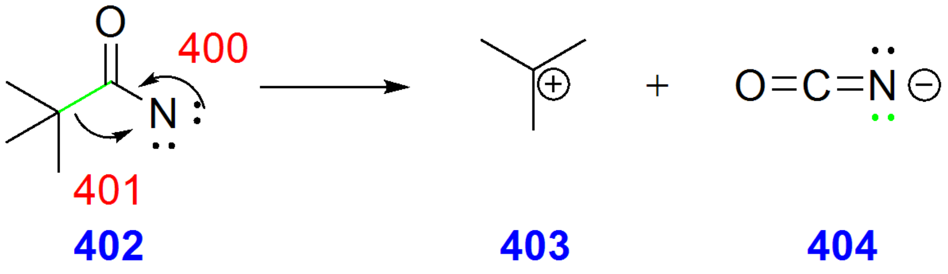
Key Principles of the Electron-pushing Formalism
1) Electron-pushing Formalism arrows start at electrons and point to an atom or bond
2) Atoms, electrons, and charges are conserved throughout
3) Electrons stay with one of the originating atoms

Table 76. Examples of Bond-forming and transplanting processes.

Bond-forming process



Transplanting process



Section 5.2: Worksheets for the EPF arrows and key principles

The following worksheets are intended to have students understand there are three key principles and that the EPF arrows must respect the principles. The warm-up exercise is a demonstration of chemical possibilities and the associated errors, with the correct response following all three key principels. Worksheet 1 provides students the opportunity to determine whether the EPF arrow follows the key principles. Worksheet 2 builds off of worksheet 1 where the chemical possibilities are removed and students must identify the correct process. Worksheet 3 builds off the previous worksheets where only the process is given and students must draw the result of the chemical possibilities in addition to determining whether the structures are correct based off the key principles. Lastly, worksheet 4 builds off the previous worksheets by giving students the opportunity to explore other chemical possibilities and determine whether their answer is correct.

Warm up

Key principles of the electron pushing formalism

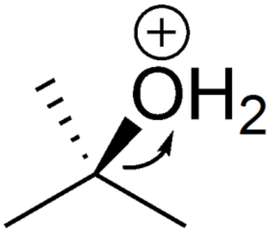
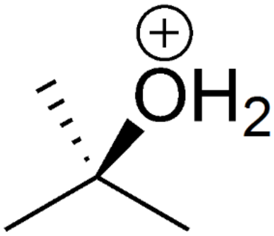
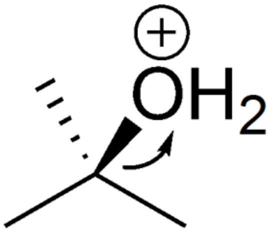
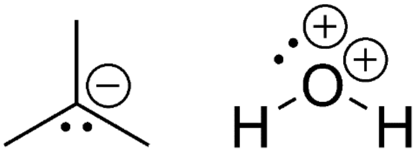
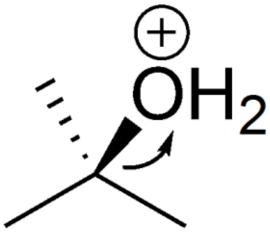
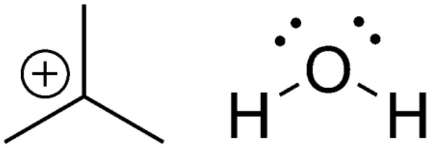
1) Electron-pushing formalism arrows start at electrons and point to an atom or bond

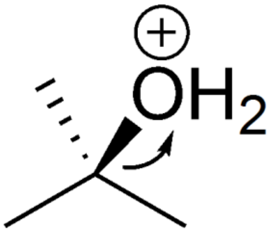
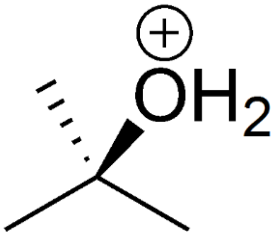
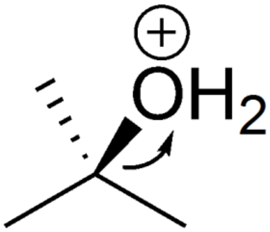
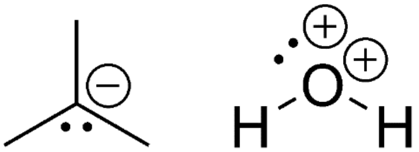
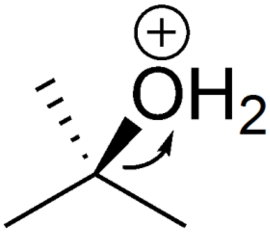
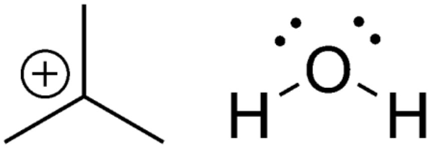
2) Atoms electrons and charges are conserved throughout

3) Electrons stay with one of the bond’s originating atoms

Do the following processes and products follow the key principles of the EPF?

Please answer yes or no if the processes and products follow the key principles and provide reasoning if they do not. The correct answer will follow all three correct principles, while the incorrect answer will break one of the key principles.

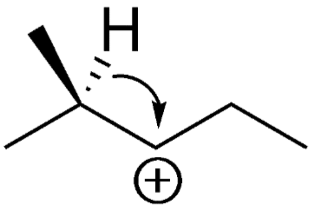
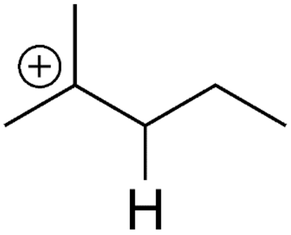
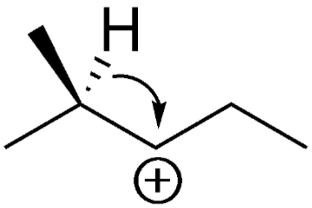
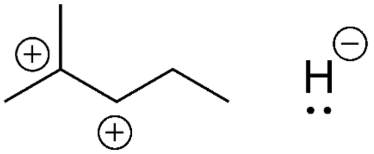
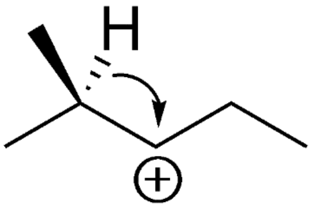
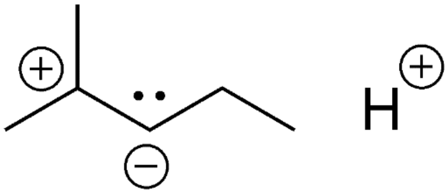
Reaction Carbocation formation	Process and products	Follows key principles?
	Bond-forming 	1. 2. 3.
	Bond-breaking electrons moving towards arrow tail 	1. 2. 3.
	Bond-breaking and electrons moving towards arrowhead 	1. 2. 3.

Reaction Carbocation formation	Process and products	Follows key principles? (Key)
	Bond-forming 	4. Yes 5. Yes 6. Yes The Carbon-oxygen bond is already bonded together. The bond-forming product has no change, therefore making it redundant and illogical
	Bond-breaking electrons moving towards carbon atom 	1. Yes 2. No 3. Yes carbon has the electron pair Bond-breaking and giving the electrons to oxygen does not follow principle 2 making it the process illogical
	Bond-breaking and electrons moving towards arrowhead 	1. Yes 2. Yes 3. Yes Oxygen keeps the electrons Bond-breaking and electrons moving follows all principles making it the logical process

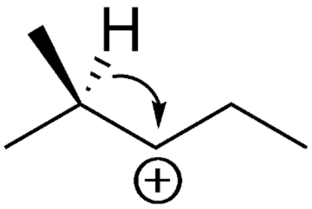
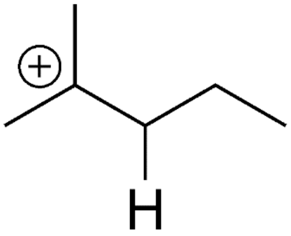
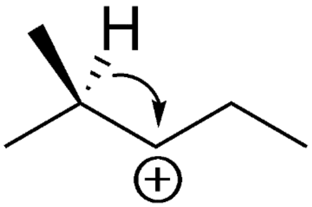
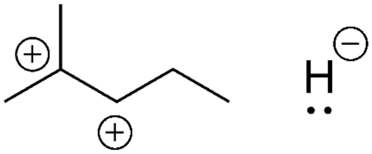
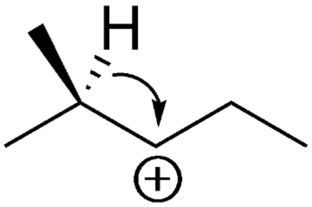
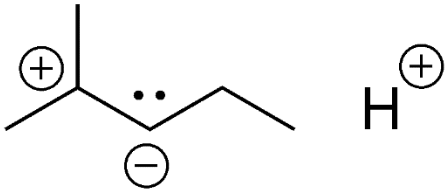
Worksheet 1

Determine which is the correct process and products by using the key principles. If one of the processes does not follow the key principle, please explain why.

The correct answer will follow all three key principles, while the incorrect answers will break one of the principles.

Reaction (1,2- Hydride shift)	**Process and products**	**Follows key principles? (not provided)**
	Bond-forming 	1. 2. 3.
	Bond-breaking and electrons moving towards hydrogen atom 	1. 2. 3.
	Bond-breaking and electrons moving towards arrowhead 	1. 2. 3.

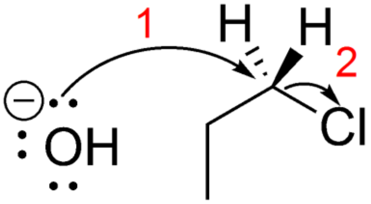
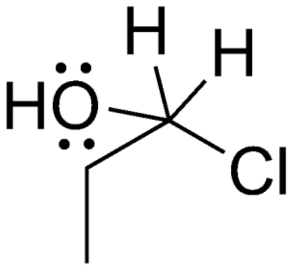
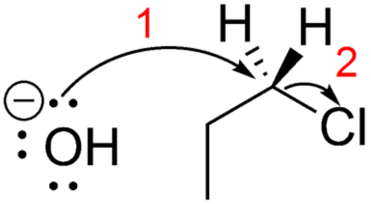
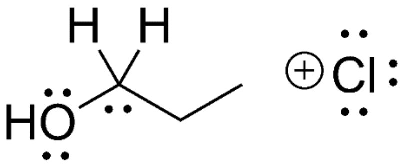
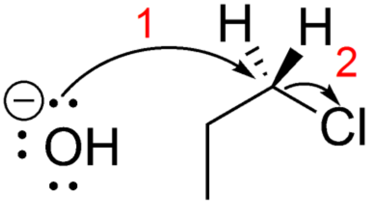
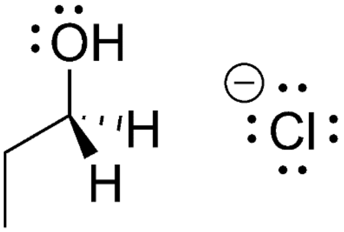
Worksheet 1 Key

Reaction (1,2- Hydride shift)	Process and products	Follows key principles? (not provided)
	Bond-forming 	1. Yes 2. Yes 3. Yes Follows all three key principles making it the logical process
	Bond-breaking and electrons moving towards hydrogen atom 	1. Yes 2. No 3. No Bond-breaking and electrons moving towards carbon atom does not follow principles 2 and 3 and creates a pentavalent carbon, making it the illogical process
	Bond-breaking and electrons moving towards arrowhead 	1. Yes 2. No 3. Yes Hydrogen kept the electrons Bond-breaking and giving the electrons to hydrogen does not follow principle 2 making it illogical

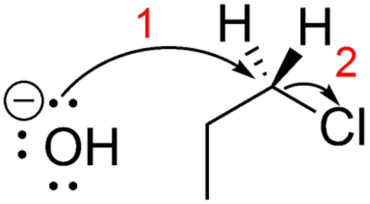
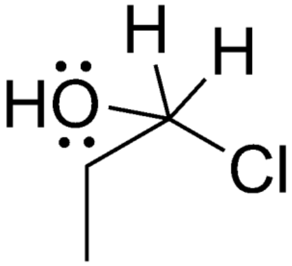
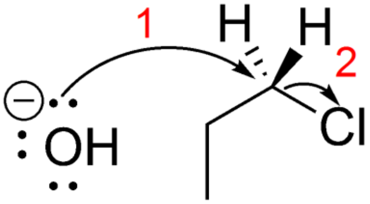
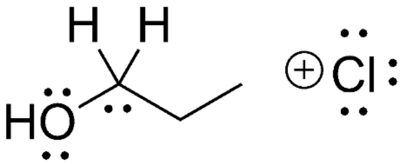
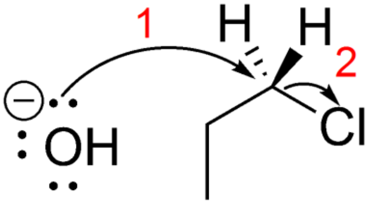
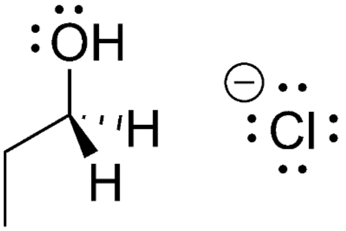
Worksheet 2

What are the chemical processes and do they follow the key principles?

Please explain your answer using the key principles.

Reaction **S_n2**	**Process and products Of EPF arrows 1 and 2** **(Process not provided)** **Structures provided**	**Follows key principles?** **(not provided)**
		1. 2. 3.
		1. 2. 3.
		1. 2. 3.

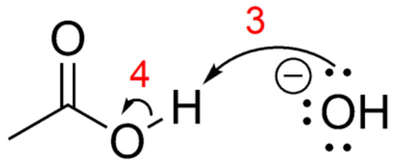
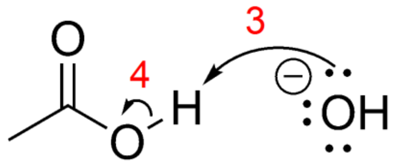
Worksheet 2 Key

Reaction S_n2	Process and products Of EPF arrows 1 and 2 (Process not provided) Structures provided	Follows key principles? (not provided)
	EPF arrow 1 – Bond forming EPF arrow 2 - Bond-forming 	1. Yes 2. No 3. Yes The bond-forming process does not follow principle 2 and contains a pentavalent carbon making the process illogical
	EPF arrow 1 – Bond forming EPF arrow 2 - Bond-breaking and electrons moving to the arrow tail 	1. Yes 2. No 3. Yes Pentavalent carbon made and does not follow principle 2
	EPF arrow 1 – Bond forming EPF arrow 2- Bond-breaking and electrons moving to the arrowhead 	1. Yes 2. Yes 3. Yes Carbon-Chlorine bond-breaking and moving the electrons towards the chlorine is the logical process

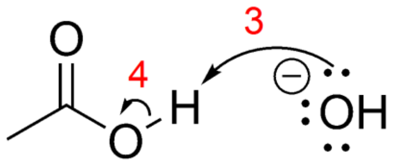
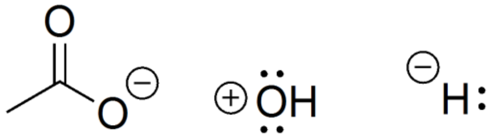
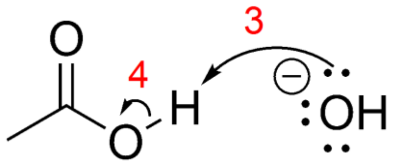
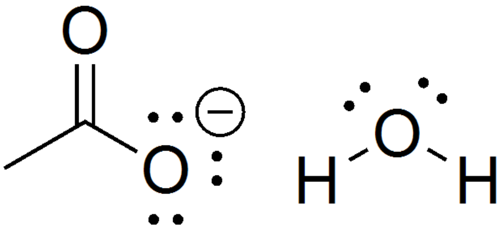
Worksheet 3

What are the products of the processes, and do they follow the key principles?

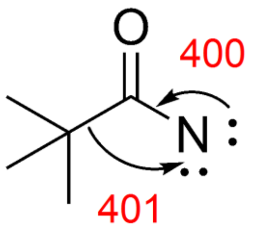
Which is the correct process and why?

Reaction (Acid-Base)	Process and product of EPF arrows 3 and 4 (Product not provided) Processes provided	Follows key principles? (not provided)
	EPF arrow 3 – Pair of electrons on oxygen is given to the hydrogen EPF arrow 4 – Bond breaking and electrons moving towards oxygen	1. 2. 3.
	EPF arrow 3 – Pair of electrons on oxygen is bonding to the hydrogen EPF arrow 4 – Bond breaking and electrons moving towards oxygen	1. 2. 3.

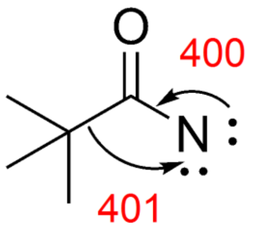
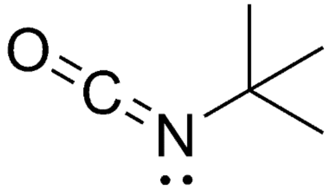
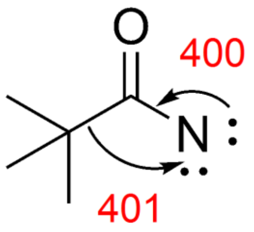
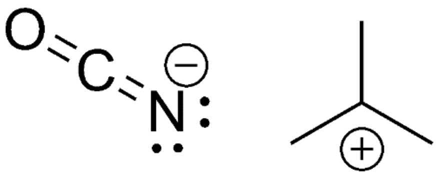
Worksheet 3 Key

Reaction (Acid-base)	rocess and product of EPF arrows 3 and 4 (Product not provided) Processes provided	Follows key principles? (not provided)
	EPF arrow 3 – Pair of electrons on oxygen is given to the hydrogen EPF arrow 4 – Bond breaking and electrons moving towards oxygen 	1. Yes 2. No 3. No Multiple charges are created and the oxygen’s electrons do not stay with the originating atom
	EPF arrow 3 – Pair of electrons on oxygen is bonding to the hydrogen EPF arrow 4 – Bond breaking and electrons moving towards oxygen 	1. Yes 2. Yes 3. Yes The bond-forming process is the logical process

Worksheet 4 – Explore possibilities and determine what EPF 401 is illustrating

Reaction **Curtius rearrangement**	**Process and product of EPF 401 and 402 (Product and processes not provided)**	**Follows key principles? (not provided)**
		1. 2. 3.

Worksheet 4 Key

Reaction **Curtius rearrangement**	**Process and product of EPF 401 and 402 (Product and processes not provided)**	**Follows key principles? (not provided)**
	EPF arrow 400 – Bond forming EPF arrow 401 – Bond breaking and forming 	1. Yes 2. Yes 3. Yes All three principles are followed making the bond-forming process the logical pathway
	EPF arrow 400 – Bond forming EPF arrow 401 – Bond-breaking and electrons moving to the nitrogen atom 	1. Yes 2. No 3. No Breaking the carbon-carbon bond and moving the electrons onto the nitrogen does not follow principles 2 and 3 making it illogical

Section 5.3: Examples for teaching reactions concertedly

Most participants in this study found it easier to interpret the EPF arrows one after another, but within a single mechanistic step, all EPF arrows occur simultaneously. The following reactions are intended to have students become comfortable with a concerted interpretation of the EPF arrows. The first reaction is a unimolcular nucleophilic substitution reaction with one EPF arrow per step, resulting in two steps with two EPF arrows (Figure 16). The following bimosubstitution nucleophilic substitution can be used to increase the difficulty and show two EPF arrows occurring simultaneously through the transition state, illustrating both a bond being formed and broken within a single mechanistic step (Figure 17). The last reaction, electrophilic aromatic substitution, illustrates four EPF arrows occurring within a single mechanistic step and can be used to demonstrate that any number of EPF arrows can occur simultaneously (Figure 18).

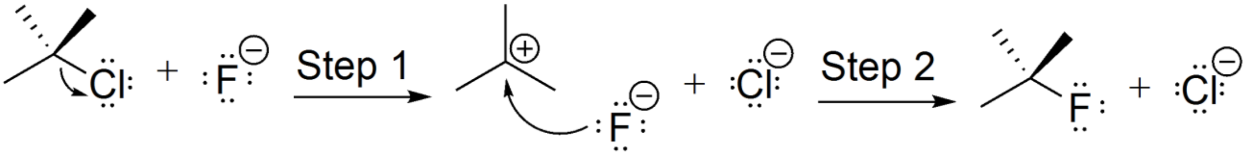


Figure 16. Unimolecular nucleophilic substitution reaction.

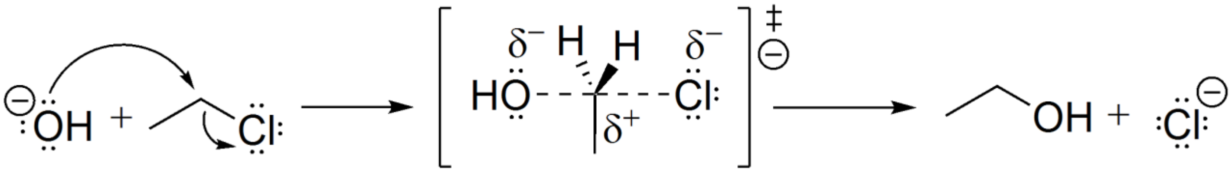


Figure 17. Bimolecular nucleophilic substitution, with the transition state to show both a bond being formed and broken simultaneously.

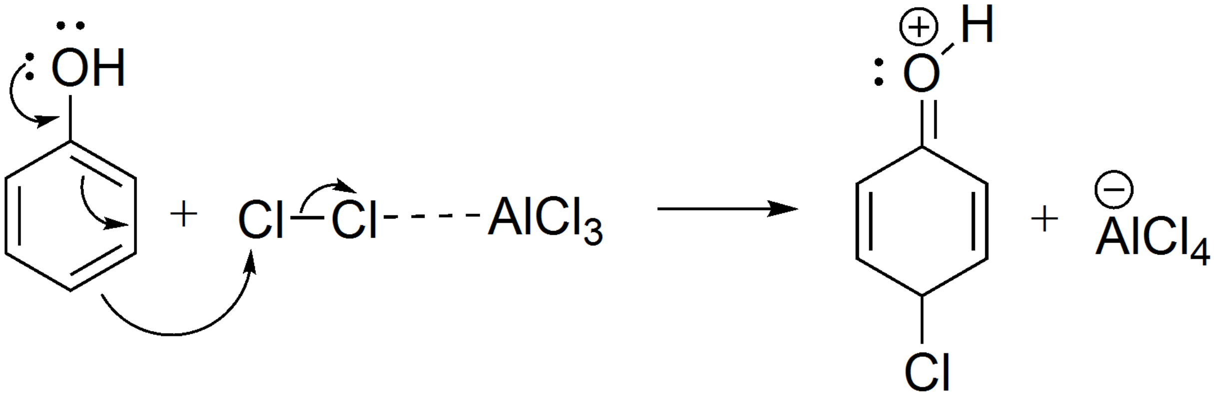
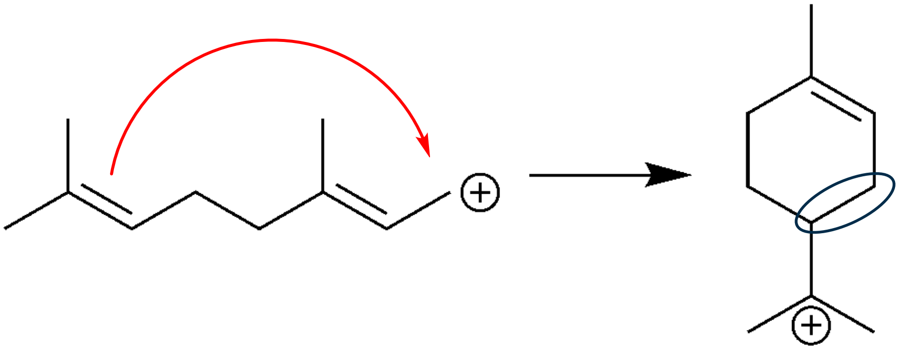


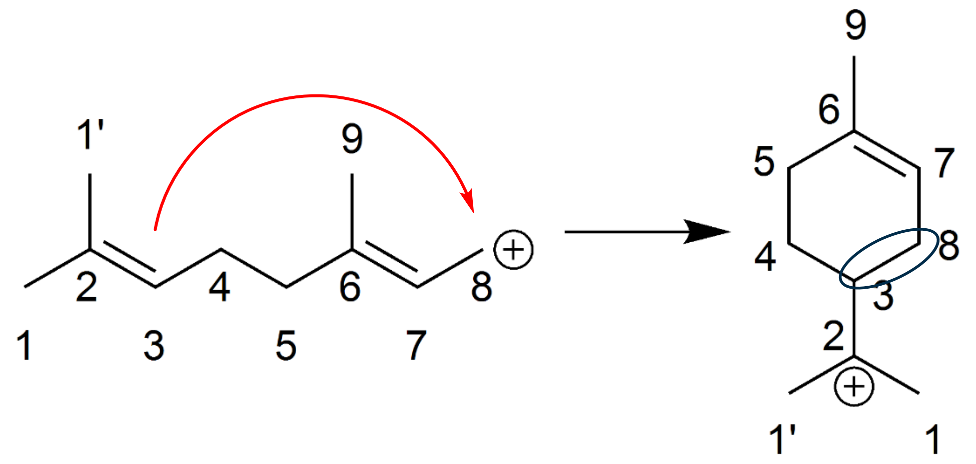
Figure 18. Electrophilic aromatic substitution illustrates four EPF arrows occurring simultaneously within a single mechanistic step.

Section 5.4: Worksheets for mapping

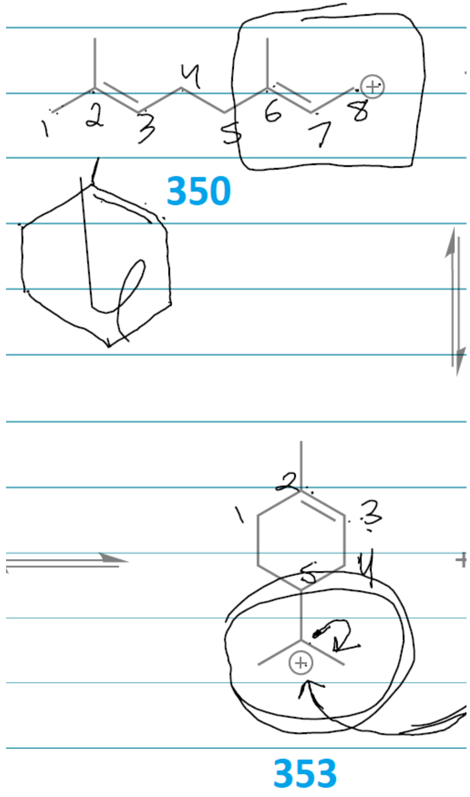
There was minimal physical mapping evidence suggesting participants did not find the physical act of mapping atoms helpful, participants did not see the value of the physical labels, or participants did not learn how to map. Participants may not see the physical labels' value when mapping as they only started learning about the EPF. The results point to a greater need for experience with the EPF arrows and mapping as a strategy to solve organic chemistry reactions. Teaching the mapping strategy through scaffolding can be used to help students see the value of physical labels. Table 77 illustrates a reaction without the mapping strategy, with the mapping strategy and common misconception. When teaching, provide the no-mapping strategy first as an example of difficulty and then the mapping strategy as an example of ease, emphasizing that physical labels are associated with higher success rates (Bodé and Flynn, 2016). Educators should map every atom in the reaction to demonstrate the value of physical labels using the common misconception that the first alkene in the reactant is the first alkene in the product to demonstrate how errors can occur with the strategy. Educators can use the common misconception to demonstrate other possible mappings and that students should be open to other possibilities.

Table 77. Implications for teaching and learning regarding the mapping strategy.

No mapping strategy used

Mapping strategy used



Common misconception



Educators can slowly remove the mapping labels from the reactant or product and provide only a few explicit labels in the reactant or product to scaffold learning. Scaffolded mapping strategy #1 provides the mapping for three atoms in the reactants and four in the products (Table 78). The question is designed for students to recognize that the first alkene may not be the first alkene in the product as they are explicitly labelled differently. Students then must decide how they would translate the reactant onto the product to determine that carbon 3 bonds with carbon

8. A similar style of question can be used where participants must decide how they would continue to map a structure. Scaffolding strategy #2 asks learners to decide how they would continue their line structure through labels to determine the correct bonding location (Table 79). Learners will have to decide which carbons are attached to carbon 3 to solve the question. A variation of strategy #2 can be used where the product structure is flipped horizontally and learners will have to decide how to connected carbon 3 to the other carbon atoms. The mapping labels on the structures could be scaffolded to be removed completely, with points being awarded for applying the mapping strategy on assignments and examinations. Another type of a mapping assessment could have participants translate the a structure from a 2-dimensional image to a 3-dimenional using explicit labels (Table 80).

Please label all atoms with numbers and determine the bonding location through your labels.

Table 78. Scaffolded mapping assessment #1.

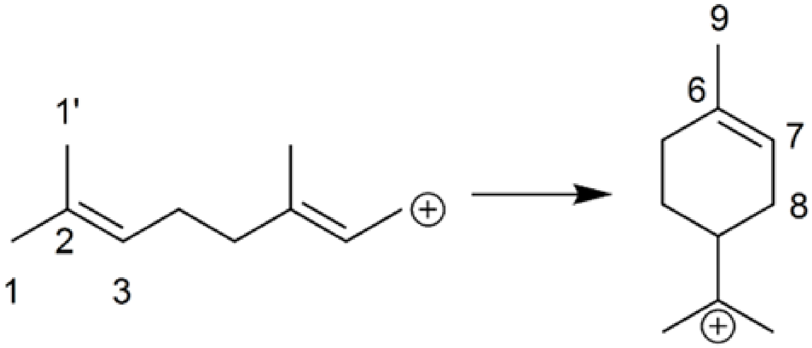
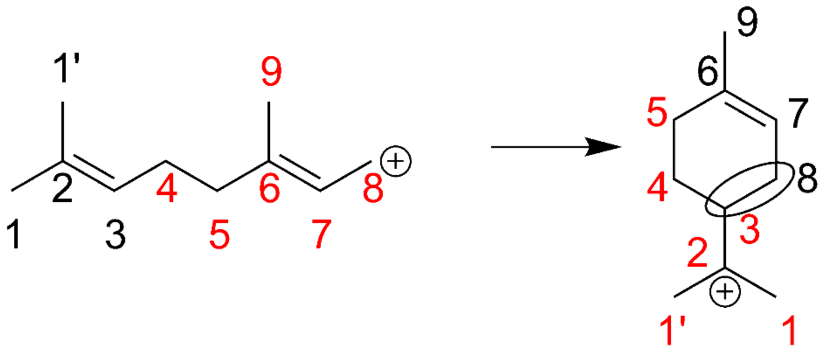
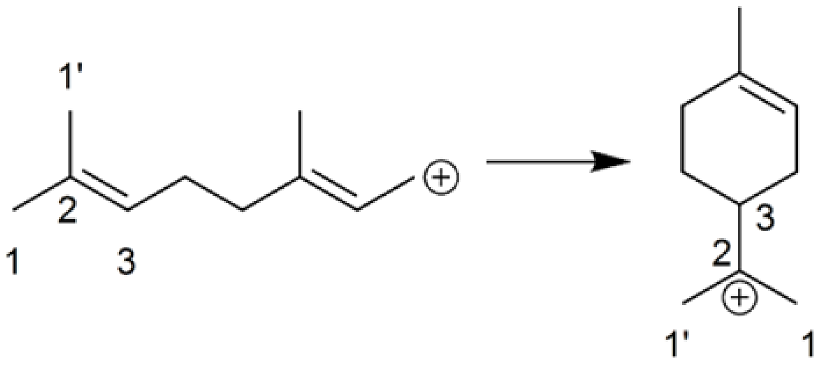
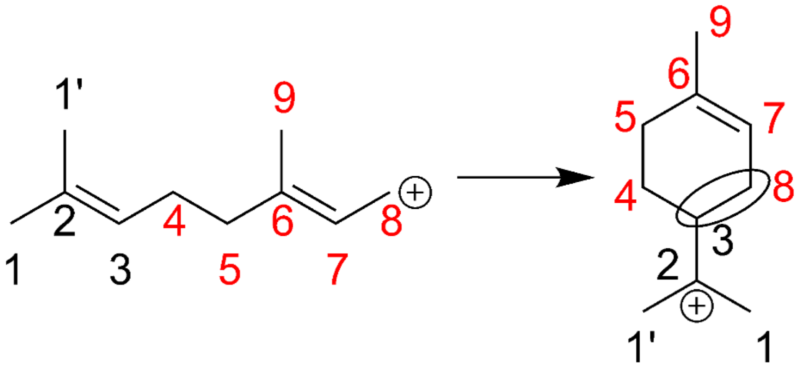
Scaffolded mapping assessment #1

Scaffolded mapping assessment #1 Key


Table 79. Scaffolded mapping assessment #2 & flipped horizontal product.

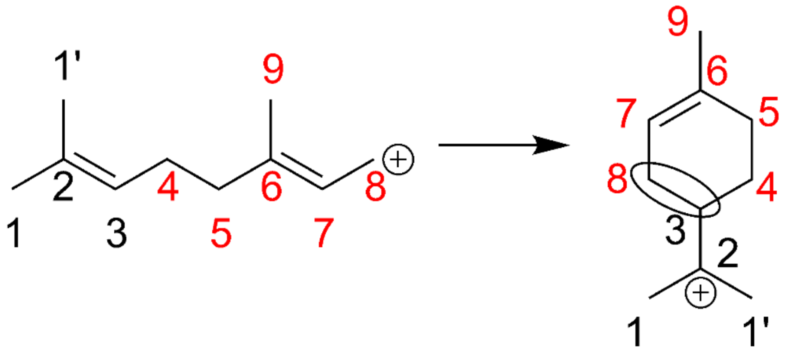
Scaffolded mapping assessment #2



Scaffolded mapping assessment #2 key



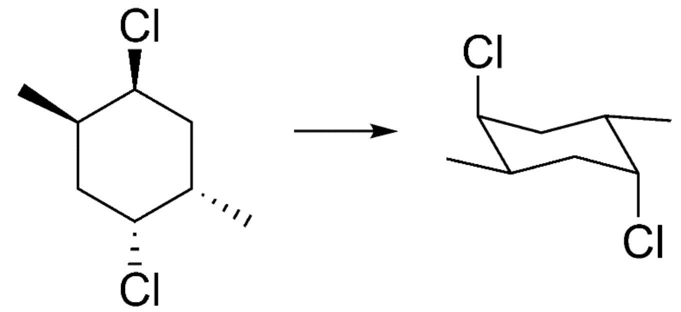
Scaffolded mapping assessment #2
Flipped horizontal product



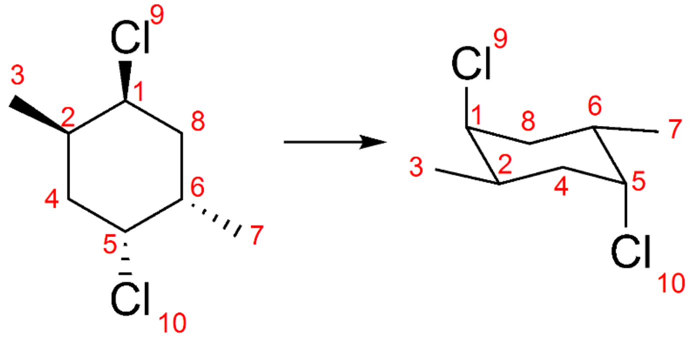
Please map the 2-dimensional structure into a 3-dimensional structure

Table 80. 2-Dimensional to 3-Dimensional mapping assessment.

2-Dimensional to 3-Dimensional mapping assessment



2-Dimensional to 3-dimensional mapping assessment key



Organic chemistry can lead to the improvement of pharmaceuticals, polymers, and materials. Mastering the EPF arrows in organic chemistry would be beneficial to students continuing in biochemistry or medicinal chemistry because the EPF is prevalent. Mastering the EPF arrows in organic chemistry would give learners more time to focus on the biochemistry or medicinal chemistry concepts without the EPF arrows being a hindrance.

The standard symbols used outside of organic chemistry may be a barrier to learning for teaching and learning within other domains of education. Educations should emphasize how to interpret the symbols by providing the purpose, meaning, and interpretations. Educators should provide problem-solving solutions when facing difficulties and emphasize being open to new possibilities.

Section 5.5: Implications for future research

The discussions and drawings participants gave provided a suggestion for future areas of research. The participants were novices and successfully determined whether a bond was broken but faced difficulty when determining whether a bond was forming. The data demonstrates participants are interpreting the EPF arrows as bond-forming or breaking processes as the revised curriculum intended (Flynn and Ogilvie, 2015). Further research could look at a larger sample size of students' initial interpretations of the EPF arrows, because 12 participants may have only covered a fraction of initial interpretations. Most participants discussed mapping verbally without labels, and research could further investigate if the physical act of labelling the atoms affects success rates.

Participants' described that a stepwise interpretation was easier to understand, but teaching organic chemistry reactions stepwise may reinforce an incorrect understanding. Thus, further research could explore why students find it easier to interpret reactions stepwise or why students find the concerted interpretation challenging. Participants have only just learned about the EPF arrows and might not have had enough time to develop an internal representation of the EPF arrows. Additional research is needed to see how students develop their understanding of the EPF when experience is gained. Participants would need to be interviewed periodically throughout their organic chemistry career using the same instrument to compare the difference in knowledge at each timepoint. Using the same instrument will allow for direct comparison, while the longitudinal factor will illustrate when participants have mastered the EPF arrows. Additional reactions can explore participants' reasoning and interpretation of EPF arrows they have not encountered.

The participants' discussion of the EPF arrows suggests that participants interpret the EPF arrows as a whole. Further research could look at if students interpret the EPF arrow as a whole or if they interpret the arrowhead and arrow tail. Whether the time spent mastering the EPF arrows at the beginning of the course is beneficial to student learning in organic chemistry. Why do some students face difficulty when conserving atoms, electrons, and charges. Why do some students face difficulty when keeping electrons on an originating atom.

Section 5.6: Limitations

This study aimed to understand how students initially interpret organic chemistry representations. All of the findings are specific to the participants in this study and should not be used to generalize student interpretations. Participants in this study provided valuable information regarding their initial interpretations of the EPF arrows and other symbolisms used in organic chemistry. However, a significant limitation of this work was the interview transcripts contained determiner words such as "this" or "that" without explicit labels meaning students' discussions could not be correlated to their drawings. Given the small sample size and qualitative nature, this work might have only captured a fragment of initial interpretations. All participants verbally mapped, but it was difficult to determine which atoms were discussed due to the lack of explicit referencing. I used data from students who gave explicit evidence. Question order may have played a role in student interpretations as a concerted interpretation was most common on question 1, while a stepwise interpretation was most common on questions 5 and 6. The question task could also play a role as question 1 was an explanation of a reaction, while questions 5 and 6 tasked participants to interpret the EPF arrows and draw a product. It is unclear whether the type of reaction, the task, or the ordering of questions played a role in participants' interpretations. However, the results are promising as participants interpreted the EPF arrows with minimal experience, aligned with the curriculum's intentions.

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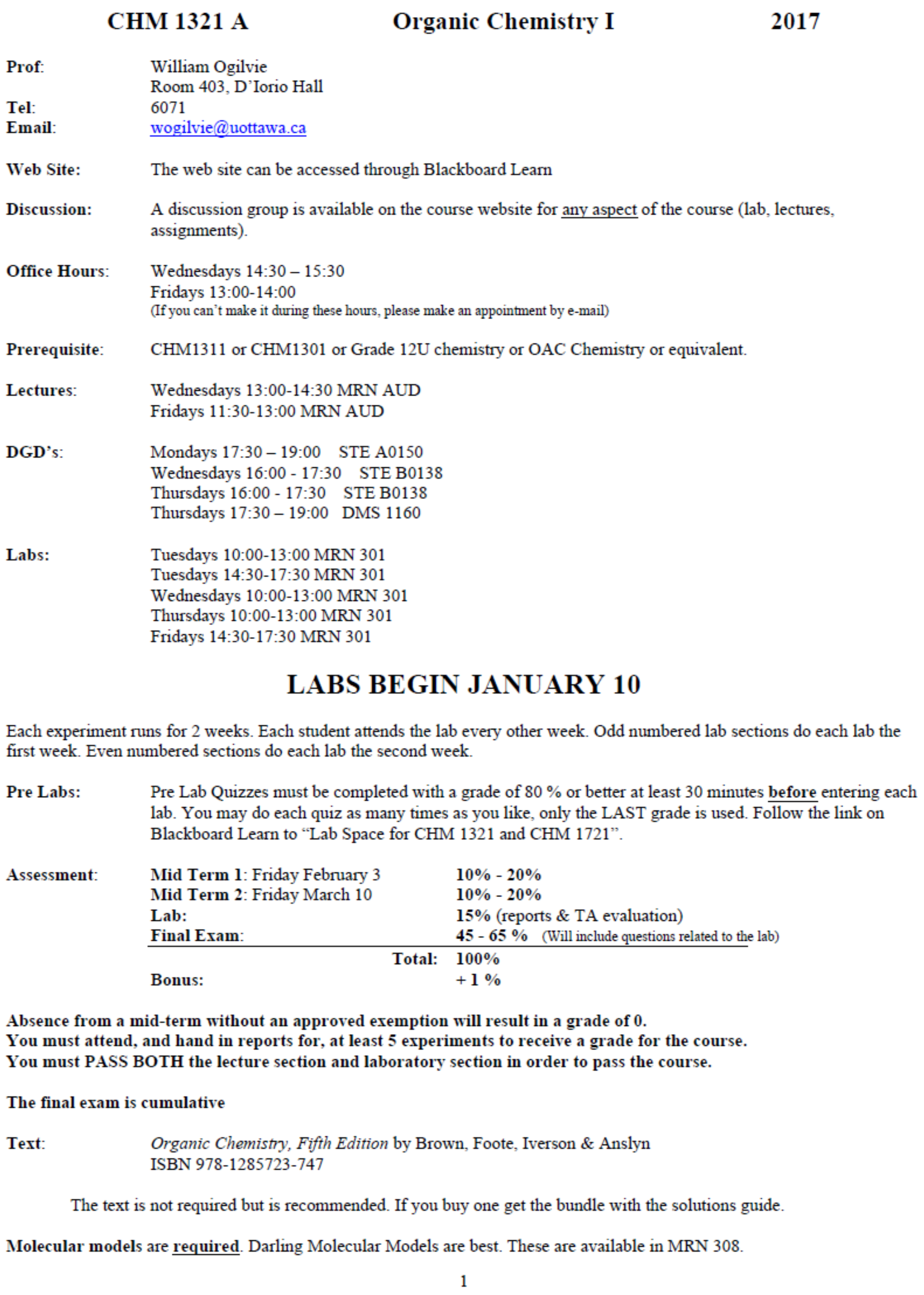
Appendix 1: CHM 1321 Course syllabus from Winter 2017 and Calendar from 2019



CHM 1321 A Organic Chemistry I 2017

Prof:	William Ogilvie Room 403, D'Iorio Hall
Tel:	6071
Email:	wogilvie@uottawa.ca
Web Site:	The web site can be accessed through Blackboard Learn
Discussion:	A discussion group is available on the course website for any aspect of the course (lab, lectures, assignments).
Office Hours:	Wednesdays 14:30 – 15:30 Fridays 13:00-14:00 (If you can't make it during these hours, please make an appointment by e-mail)
Prerequisite:	CHM1311 or CHM1301 or Grade 12U chemistry or OAC Chemistry or equivalent.
Lectures:	Wednesdays 13:00-14:30 MRN AUD Fridays 11:30-13:00 MRN AUD
DGD's:	Mondays 17:30 – 19:00 STE A0150 Wednesdays 16:00 - 17:30 STE B0138 Thursdays 16:00 - 17:30 STE B0138 Thursdays 17:30 – 19:00 DMS 1160
Labs:	Tuesdays 10:00-13:00 MRN 301 Tuesdays 14:30-17:30 MRN 301 Wednesdays 10:00-13:00 MRN 301 Thursdays 10:00-13:00 MRN 301 Fridays 14:30-17:30 MRN 301

LABS BEGIN JANUARY 10

Each experiment runs for 2 weeks. Each student attends the lab every other week. Odd numbered lab sections do each lab the first week. Even numbered sections do each lab the second week.

Pre Labs:	Pre Lab Quizzes must be completed with a grade of 80 % or better at least 30 minutes **before** entering each lab. You may do each quiz as many times as you like, only the LAST grade is used. Follow the link on Blackboard Learn to "Lab Space for CHM 1321 and CHM 1721".

Assessment:

	Mid Term 1: Friday February 3	**10% - 20%**
	Mid Term 2: Friday March 10	**10% - 20%**
	Lab:	**15%** (reports & TA evaluation)
	Final Exam:	**45 - 65 %** (Will include questions related to the lab)
	Total:	**100%**
	Bonus:	**+ 1 %**

Absence from a mid-term without an approved exemption will result in a grade of 0.
You must attend, and hand in reports for, at least 5 experiments to receive a grade for the course.
You must PASS BOTH the lecture section and laboratory section in order to pass the course.

The final exam is cumulative

Text:	*Organic Chemistry, Fifth Edition* by Brown, Foote, Iverson & Anslyn ISBN 978-1285723-747

The text is not required but is recommended. If you buy one get the bundle with the solutions guide.

Molecular models are **required**. Darling Molecular Models are best. These are available in MRN 308.

1

Course Outline

Nomenclature: *Do it yourself.* You are responsible for naming chains up to 12 carbons long for all classes of compound covered (alkanes, alkenes, alkynes, alcohols, thiols, halides, amines, aldehydes, ketones, ethers, cyclic and acyclic molecules). You are NOT required to name bicyclic compounds (section 4.4B). A guide to nomenclature is available on the course web site. Pages 142-154 in the text cover the basics of nomenclature. You should use the index to find rules for selected functional groups.

Part A: Structure

1) Organic Molecular structure
   a. "Organic" periodic table, electronegativity and periodic trends, covalent bonds
   b. Drawing organic structures: Lewis & compressed structures, formal charge method, polarity, resonance
   c. Atomic and molecular orbitals, molecular orbital theory, bonding and antibonding orbitals
   d. Orbital shapes and hybridization. Bond angles and structure, σ and π bonds, geometries, relative energies
   e. Dipoles, Van der Waals forces, H-bonding. Molecular structure and bulk properties
2) Alkanes
   a. Properties, line structures, σ bond rotation, conformations, energy potential diagrams, Newman projections
   b. Cycloalkanes, ring strain, conformations, configurations, syn/anti and cis/trans nomenclature.
   c. Chair conformation, axial and equatorial bonds, chair interconversions.
   d. Stereochemistry, configuration and R/S nomenclature, enantiomers, diastereomers and meso compounds,
   e. Zig-zag structures, syn/anti nomenclature, resolution, optical activity, enantiomeric excess.

Part B: Simple Reactivity

1) Acids and bases
   a. Acid/base reactions, acidity of organic compounds, inductive effects, resonance, periodic trends. Use of pKa values
   b. Functional groups, arrow notation, reaction co-ordinate diagrams.
2) π Bonds as electrophiles
   a. Polarity of π bonds. Carbonyl compounds. Effects of resonance. Concept of mechanism, nucleophiles, electrophiles.
   b. Reduction of carbonyl groups. Additions "across" π bonds. Sodium borohydride and lithium aluminum hydride.
   c. Imines. Acid catalysis. Sodium cyanoborohydride.
   d. Cyanohydrin formation. Reversal of the reaction. Acid and base catalysis
   e. Grignard reagents. Preparation. Polarity. Acid/base reactions. Carbonyl displacements.
   f. Organo-lithiums. Acid/base reactions. Carbonyl displacements. Alkynyl and vinyl nucleophiles.
   g. Hydrate formation. Equilibrium with carbonyl forms. Hemi-acetal formation. Intramolecular reactions and ring formation.
   h. Acid and base catalysis in carbonyl additions. Oxonium ions. Additions to oxoniums.
   i. Microscopic reversibility. Molecular orbitals and reactivity

Part C: π Bonds and Reactivity

1) π Bonds as nucleophiles
   a. Markovnikov additions. Hydration. Oxy-mercuration. Regioselectivity
   b. Anti-Markovnikov additions. Hydroboration. Stereochemistry.
   c. Radical hydrohalogenation. Chain reactions and initiation.
   d. Epoxide formation. Concerted mechanisms. Stereochemistry.
   e. Halogenation. Stereochemistry. Halohydrin formation. Regiochemistry.
2) Aromatic compounds as nucleophiles
   a. Aromaticity. Huckle rule. Antiaromatic compounds. Ions and heterocycles.
   b. Allyl groups and resonance. Allyl cation and anion.
   c. Electrophilic aromatic substitution. Directing groups. Electrophiles. Heterocycles.
   d. Manipulations of directing groups. Reductions. Hydrolysis.
   e. Multi-step synthesis. Retrosynthetic analysis. Disconnections.
   f. Allyl and Benzyl radicals. Benzylic ions and radicals. Control in radical reactions.

CHM1321: WINTER 2019

JANUARY 2019

S	M	T	W	T	F	S
		1	2	3 Semester begins	4	5
6	7 Courses begin	8 Intro	9	10	11 Bonding	12
13	14	15 Bonding	16	17	18 Bonding	19
20	21	22 Alkanes	23	24	25 Last day to add Alkanes	26
27 A0/A1	28	29 Stereochem	30	31		

FEBRUARY 2019

S	M	T	W	T	F	S
					1 Stereochem	2
3 A2	4	5 Stereochem/ Mechanisms	6	7	8 Mechanisms	9
10 A3	11	12 Acid-Base chem	13	14	15 Acid-Base chem QUIZ	16
17	18	19	20	21	22	23
24 A4	25	26 π as E+	27	28		

MARCH 2019

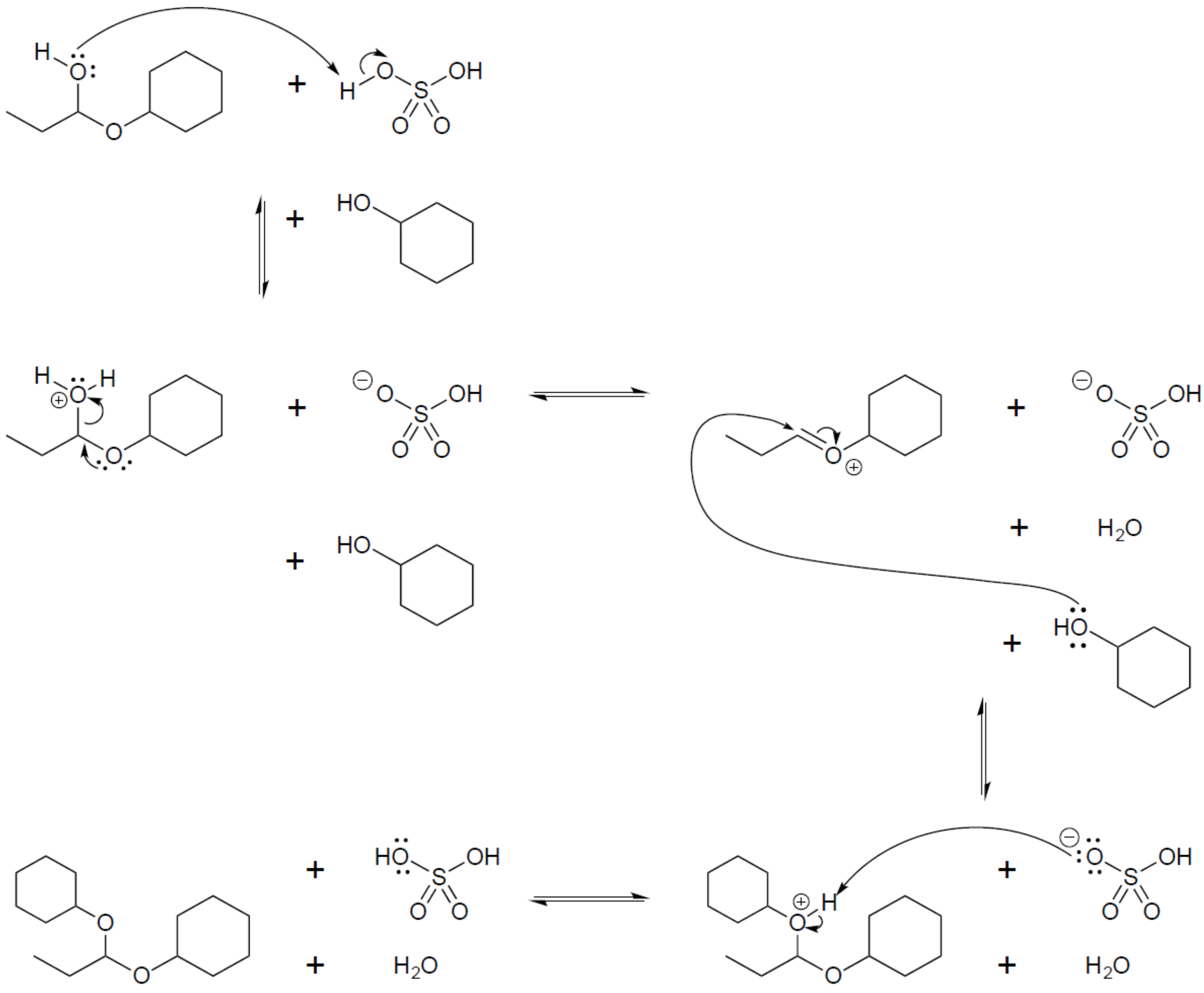
S	M	T	W	T	F	S
					1 π as E+	2 Midterm 1
3 A5	4	5 π as E+	6	7	8 π as E+	9
10 A6	11	12 π as E+	13	14	15 π as Nu	16 Open House 🏛
17 A7	18	19 π as Nu	20	21	22 Drop Day π as Nu	23 Midterm 2
24 A8	25	26 π as Nu/ Aromatics	27	28	29 Aromatics	30

APRIL 2019

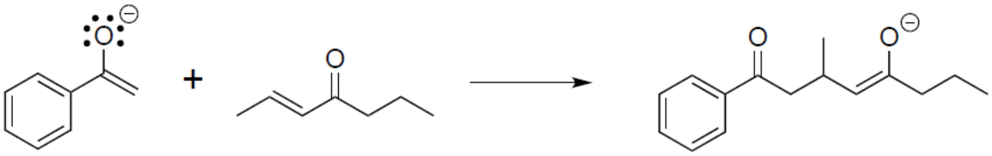
S	M	T	W	T	F	S
31	1	2 Aromatics	3	4	5 Courses End Review	6
7 A9	8 No Classes	9	10	11	12	13
14 A10	15	16	17	18	19	20
21	22	23	24	25 Exams end	26	27
28	29	30				

Appendix 2: Instrument - Interview Tasks

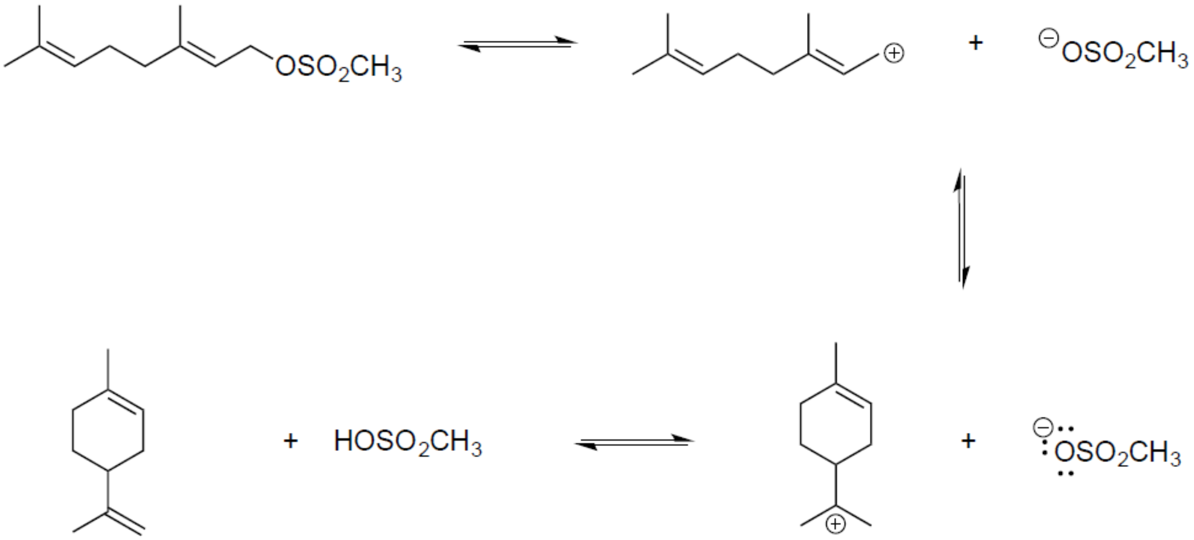
Q1: Explain



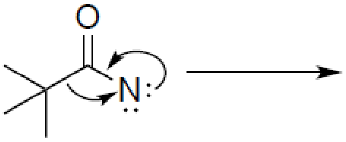
Q2: Add curved arrows



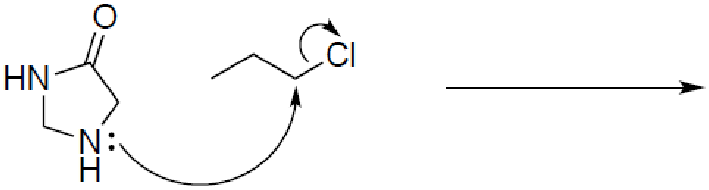
Q3: Add curved arrows



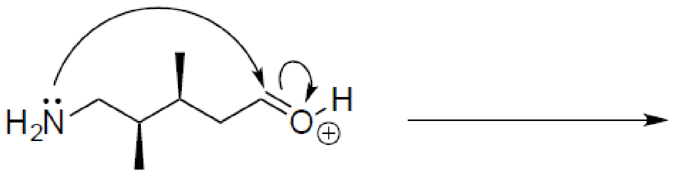
Q4: Draw the product



Q5: Draw the product



Q6: Draw the product



Appendix 3: Interview Guide

Interview Checklist

- Student consented to participate
- Interview scheduled and confirmed
- Interview space reserved
- Materials gathered:
    - Livescribe pen, charged
    - Interview tasks printed on Livescribe Dot paper
    - Voice recorder with charged battery and memory space
    - Notepad to take notes
    - Regular pens
    - Periodic table
    - Model kit
- Give gift card and have sign compensation received form

The bulleted statements below are the introduction and confidentiality discussion before the actual interview begins. This is not necessarily a script. The bulleted points outline what will be discussed. Italicized below each bullet is an example of each bulleted conversation.

- Thank the student for participation
    - *"I want to begin by thanking you for coming today. Your participation in this study is very important to me, and I want you to know that your time and effort are very much appreciated. Here is your gift card. Please sign this form stating you received the gift card."*
- Ask student to read consent form
    - *"I want you to take a minute and read through the consent form in front of you. This form will outline your rights as a participant and the confidentially of this study. Thank you."*
- Remind student that they are allowed to quit the interview at any time.
    - *"As a reminder you are allowed to quit this interview at any point during the interview. You are also allowed to remove your participation in the study at any point before the material is published. Please just notify me through my e-mail address on the consent form and I will remove your data."*
- Reminder of confidentiality
    - *"Anything you describe to me verbally or draw will be collected at the end of the interview and used as data in my study. Your identity will be removed from all pieces of data and your name will be changed to a pseudonym for the sake of confidentiality. Your professors will not know that you participated in this study or anything that you say during this interview today so please be open and honest. This interview will not affect your grade in any way. The audio will not be played for presentation purposes because we are aware that your professors may be in the audience and may recognize your voice. If you use your professors' names during this interview, their names will also be changed to a pseudonym in order to protect you and your professors. However even when using pseudonyms, people who know you well may recognize you through the stories you tell or through phrases that are unique to your personality."*
- Explanation of audio recording confidentiality

    - *"I would like to audio record you today. The audio recording is to accurately capture our conversation here today. Is it ok with you that I audio record this interview today?"*
- Any further questions?
    - *"Do you have any further questions about the interview itself or the confidentiality of this study? Ok. If you have any further questions, you may contact the ethics review board, my research advisor, or me through the e-mail addresses attached to the consent form that you just signed. Ok. Let's begin."*
- Ending the interview
    - *"The interview will probably take 30 to 45 minutes. When is the moment when you absolutely need to leave? I will keep track of time."*

Introduction:

- Today I'm going to ask you questions regarding organic mechanisms.
- For each question, I would like for you *think aloud*—to voice what you're thinking as your solve the questions. It may seem unnatural or awkward, but just try your best.
- I'm not interested in the right answers, but I am interested in how you solve the questions.
- Even if things seem irrelevant to solving the questions, please share with me anyways.
- Throughout the interview, I may ask questions to help understand your process and how you are solving the questions.
- I have a model kit available if you would like to use at anytime.
- I will take notes throughout just so you know.
- Take your time. Work at your own pace.
- For our interview today, we are going to use a Livescribe Smart pen. This pen will record what you draw with what you say. To get started, all you need to do is tap the record button at the bottom of this first page.

Task 1: Explain Mechanism

- For this first task, please explain to me what you see on the page.
- You are welcome to draw or annotate as much as you would like.

Task 2: Draw Arrows

- For the second task, please draw in the arrows for the reaction shown.
- You may also need to draw electrons, expand bonds, or make other drawings to complete the task.
- Remember as you solve the problem to tell me about your thought process.

Task 3: Draw Arrows

- The third task is also a Draw Arrows question. Please draw in the arrows for the reaction shown below.

Task 4: Draw Products

- For the fourth task, please draw the product or products for the reaction for the given reactant and reaction arrows.

Task 5: Draw Products.

- For our fifth task, please draw the product or products for the reaction.
- Build a model.
    - How do you think this reaction happens?
    - Why do you think this reaction happens?

Task 6: Draw Products.

- For our last task, please draw the product or products for the reaction.
- Build a model.
  - How do you think this reaction happens?
  - Why do you think this reaction happens?

Closing Remarks

- Is there anything else you would like to share with me about the tasks we have worked through today?
- Thank you for your time. I greatly appreciate it.

Pay attention to:	**Potential question(s) to ask:**
Mapping vs. labeling	What are you thinking about as you number the atoms? Is there a method to the numbering?
Students use of charge	How do you use charge to solve the problem? How important is charge to you in solving the problem?
Identification of reaction sites	How do you identify where a reaction will take place?
What driving forces do students identify?	What tells you a reaction will occur?
Stepwise – problem solving strategy or actual addition intermediate? Order of arrows vs. concerted? “This, then this, then this, etc.”	Are you thinking about the order of the arrows? How does this process happen in your mind? How are you picturing this reaction happening in your head?
What prior knowledge do students use and when?	How do you know? Tell me more about [chemistry concept mentioned]…
Transplanting electrons – why and when?	How do you know the electrons go there? What tells you the electrons go there?
Use of model kit – why not?	Would a model kit help you solve this problem? How do you decide when to use the model kit? If you do decide to use a model kit, how do you use it? Do you have any strategies or do you play around until you figure out the problem?
How do students determine if bond can break or form?	How do you know that is the bond that breaks? How do you know that is the bond that forms? What information on the page tells you that?

Note taking fillers & probing questions:

- I’m going to take notes throughout.
- Give me a second. That was really interesting.
- Please tell me more about that.
- What do you mean by that?
- Could you give me an example?
- I didn’t understand that. Can you explain?

- I hadn’t thought of that perspective.
- Could you go back to…?
- Could you run that by me again? I’m afraid I still don’t understand.
- What happened that made you think that?

Things to avoid saying or asking

- Avoid using functional group names or other chemical terminology before student
- Ask only 1 question at a time. Allow time for student to answer before asking a clarifying question
- Avoid affirmative language like “perfect,” “great,” or “awesome”
- Avoid talking about mechanisms, functional groups, surface features, or other reaction related characteristics unless student brings it up. Then ask clarifying and elaborating questions.

Avoid posing an answer to a question you just asked.

Participant #01	
Q1	“An electron pair from the oxygen is pointing towards the hydrogens [Arrow 100] so that must mean there’s a, there’s a bond that’s suppose to form between both of them and the bond is supposed to break from this hydrogen, between this hydrogen and this oxygen um the electron is supposed to go to the oxygen.”
Q1	*“There’s an arrow* [Arrow 104] *from the bond um the bond to the oxygen atom which means that this bond is going to be broken and the electrons are going to go to the oxygen so that is why it this Sulphur compound ends up stealing the hydrogen. So when. Lets see um, so. So the electrons* [Arrow 103] *here goes to pair with the hydrogen. And the bond between hydrogen and oxygen gets broken* [Arrow 106] *which is why oxygen gets to keep all the electrons and it no longer has a charge* [Molecule 108].”
Q2	“Okay so the bond has to form over here. Hmm there’s a charge here so that means that theres no *inaudible* […] So that means because there’s there’s an octet here and there’s no octet here, this bond has to break to give it *inaudible*”
Q3	“so this compound is broken down into two, which means that the lets see where it’s broken it’s broken on the oxygen and the carbon so then the bond is going to go to the carbon so that you break that bond”
Q4	The electrons, the arrow is pointing from um pair of electrons here to the bond that means it’s going to form uh bond. But that doesn’t make sense because if it forms a bond over here then its going to be five bonds on the carbon that is here
Q5	“the bond is broken between here this carbon is going to have what charge because there is one two. And it’s going to have a positive again. And then this one is going to have a minus because.”
Q6	“I can make the double bond with the other carbonyl, so instead of doing a double bond here, I do a double bond from the carbon that its connected to”

Participant #02	
Q1	there’s the carbon that is attached that is going to be attached there or like. Something about this carbon bonded up here.
Q2	This carbon is oriented like upwards, and there’s the carbon that is attached that is going to be attached there or like. Something about this carbon bonded up here.
Q3	okay. Okay so this bond would be broken. Over here. So you can form your two things. I think. So from the bond, the electrons would go to the. Would become a lone pair on the oxygen
Q4	I’m guessing that might be like a bond breaking between the two carbons here.
Q5	“There is a bond broken. And there’s uh. Lone pair that comes. I guess it would just be. A lone pair on the C. there’s a lone pair on the C. and. That would mean there’s a formal charge of negative one”
Q6	“uh the arrow goes from. like in this case literally the electrons into another. To another atom. And for things that go from a bond, well things are presented in the bonds are the electrons being shared. And when that has an arrow from that to another, I assume the electrons are just moving to the other atom.”

Participant #03	
Q1	oh yeah because the charge uh to move molecules around you have to attach things, you go from having these two separate now they’re together, but to attach things together you have to use the charges and the lone pair of electrons to be able to give and receive electrons and make and form bonds.

Q2	I'm moving it straight to the bond there to make that a double bond, instead of showing it in two steps, I'm just doing it in one arrow.
Q3	Um well the arrows that are like showing the electrons moving to like, like kind of pointing at another thing shows like I guess that those two things are (then a getting)- kinda get bonded together I guess?
Q4	*"So this arrow* [Arrow 401] *shows to this bond is breaking because an arrow from a bond to an atom breaks the bond."*
Q5	*"This arrow* [Arrow 502] *here shows that this bond is breaking. Because when something is pointing from a bond to an atom, the bond is breaking. So like things point* [Arrow 501] *from electrons to an atom, the bond is being formed."*
Q6	"I'm thinking that since this is one whole molecule and when electrons are pointing to the bond pointing to an atom a bond forms and it's going to form a ring now between that nitrogen and this carbon."

Participant #04	
Q1	So the hydro- the oxygen takes the, the electrons from the bond it has between oxygen and hydrogen which leaves that hydrogen ion type thing
Q2	"Because this bond would break, yeah, yes, yes okay yes, this, okay so this, these two electrons would go here to form this double bond"
Q3	"So the bond between the oxygen and the carbon is broken, so this one has- because oxygen is more electronegative it's going to take all the electrons from the carbon"
Q4	"I think yeah this bond is being broken where these electrons, or the electron- the lone pair the elec- or whatever the electrons between the carbon and the carbon are being donated to the nitrogen instead"
Q5	"That bond between the carbon and the chlorine is being detached"
Q6	"I guess it it just shows which way the electrons are going to be moving to create bonds or breaking bonds"

Participant #05	
Q1	"Um well the arrows that are like showing the electrons moving to like, like kind of pointing at another thing shows like I guess that those two things are (then a getting)- kinda get bonded together I guess?"
Q2	I think may- oh so I think this pair of electrons here would make a double bond there
Q3	I want to say like something happened with this electron as well to make like the double bond that happens here
Q4	I think, okay maybe I'll move over to this side now, okay so it has this pair here and it's moving those now it would be a double bond
Q5	this is like the end so maybe it's got a b- like use like these are used to bond with this carbon here
Q6	And this double bond is gonna be taken away, uh yeah it's just gonna be broken to put the electrons on the oxygen

Participant #06	
Q1	"Yeah um so now, this oxygen is positive 'cause one, two, three, four, five electrons localised around it again, um so it looks like this bond breaks that it just gave to the carbon"

Q2	“I knew that the, the double bonds uh formed a bond with the oxygen rather than being given up”
Q3	“so that means that lone pair that lone pair that was formed here is going to go to this bond to create the double bond”
Q4	“So because this single bond is leaving um I'm thinking that it should be two products. Because this bond is being broken”
Q5	“Okay, so right off the bat I've seen this before, where the single bond on the chorine just goes and, uh it makes a chlorine anion”
Q6	“this double bond here is going to break to give one of its uh, give another valence pair to the oxygen”

Participant #07	
Q1	fir--the bottom one shows that the electrons are creating a bond with the next-- the carbon, the central carbon atom and then that's [sic] carbon atom is, also breaking the bonds so that re--releases water, releases water in the next -- in the next step, I suppose
Q2	I circled the electrons and moved it to the bond to crea-- to remove the negative charge and make it a double bond with the oxsygen
Q3	it’s just hanging around with nothing around it, so it is the bond is broken and that just splits into two different compounds now
Q4	Hmm, not really I mean it was pretty straight forward. The bond broke and then you move electrons over to create two compounds.
Q5	this bond just turn into a pair of electrons, connected to chlorine leaving this carbon at the end supposedly empty. So the electrons created a bond with that electrons here created a bond with that end carbon and they connected to the rest of the molecule
Q6	I saw this double bond bro- the pi bond broke and then added a pair of electrons to the oxygen filling its octet making it happy

Participant #08	
Q1	“the electrons which are forming this bond are going up to form a lone pair”
Q2	“this is the bond we’re making or like the thing we’re putting together”
Q3	“so moving these electrons and breaking these bond and moving the electrons to the “O” gives the carbon here a positive charge”
Q4	“by taking out this lone pair out and forming a bond”
Q5	“so like those lone pairs just like. Making a bond here”
Q6	“so by pulling these electrons out of this bond, we actually make, um. We just get rid of this and we get a single bond”

Participant #09	
Q1	“You're breaking bonds and making new ones so that you can um share them between the molecule I guess”
Q3	then somewhere here we lose a double bond
Q4	“It shows me that a bond is forming, or the electrons are moving”
Q5	“Okay so I have a pair of electrons that's going to this bond, so naturally you want to assume that that's gonna be a double bond that forms”
Q6	“maybe to break double bonds has something to do with it because there's a double bond there, maybe breaking that bond would allow it to change how it reacts with other chemicals”

Participant #11	
Q1	“I guess for this one [pause] okay actually for this one, um, my best guess would be um the [pause] um, the bond breaks […]And the electrons move over here which gives it a negative charge”
Q2	“So, one of the double bonds is broke into a single, um. [Pause] I think there would be an arrow leaving to the negative […] To the lone pairs here. That might be the reason for this negative charge”
Q3	“I guess there is a-a bond being broken, um for the first step. Um [pause] because of the negative and positive charges in the product”
Q4	“I want to say the bond breaks then the electron, the extra electron goes to the nitrogen to fill it again.”
Q5	“. I just want to say that um since one of the electrons from the nitrogen in the pentane, since one of those electron gets moved over it cancels out how it lost an electron when the bond broke.”

Participant #12	
Q1	“Okay. Um so we have um a hydrogen moving over to um a different molecule. So um that probably means that the um oxygen will then form a double bond with um the carbon”
Q2	“Um so in order to fix that you move um one lone pair, um to make a double bond with carbon because then you'd have two lone pairs”
Q3	“Um so what you would do is you'd have to like break this double bond […]Um but you have to keep, you still have to keep one of them charged um and so (...) um (...drawing) you would I guess like break this”
Q4	“So that means there's nothing connecting- it breaks into two molecules. Um so you have your double, your carbon double bonded to the oxygen. And then um, well you can see that a double bond is forming”
Q5	“Okay, um so there is a bond breaking between the carbon and the chlorine.”
Q6	“the electrons are moving on, like on, to the carbon […] Um but they're going to form a bond”

Participant #13	
Q1	“the electrons from this bond here are gonna go onto here which is gonna break that bond […]And then when you go onto the ele- the oxygen and these, this lone pair from the oxygen is gonna go into this bond to make a double bond”
Q2	“And I'm not sure where that extra carbon is coming from, um but I know there needs to be another bond, so if, I think that if I do something like this bond onto here, which would allow, and then this to here”
Q3	“So, I would move the first, I'm gonna draw the first arrow as the flow of electrons from this bond onto here […] So that this being like electron deficient and this one would have a lot of electrons so I'm going to do that, which breaks the bond so these two would end up separate”
Q4	“then this bond is breaking by giving electrons to the nitrogen which gives it a, quite a few electrons so it has a negative charge”
Q5	“Which, so that's gonna give more electrons to the chlorine which give it Cl, that's gonna be one of the products because it's being brok- the bond is being broken”
Q6	“I think this arrow is going to this carbon not to this bond, 'cause that wouldn't make sense um […] Okay um (laughs) okay so that means that a bond is most likely going to form between nitrogen and carbon”

Appendix 4: Language of Mechanisms Codebook

Huang, D., Galloway, K., & Flynn, A. B.

Supporting Information

Department of Chemistry and Biomolecular Sciences codebook: Language of Mechanisms Codebook

Please let me know if you disagree with the definitions/notes

This codebook is used to determine reliability and validity of results. Please work alongside this codebook as you process the transcripts. The codes have been split into a different themes. Definitions for each code have been provided along with examples.

For each code please show the example and image if it applies as well as a note if necessary. The quotes will be used as a comparison and discussion will be held in order to confirm results. The frequencies will be compared to determine whether the code has been accurately defined.

Note: some discussions may qualify for multiple codes, please count them.

Note: participants may communicate one idea multiple times throughout one question, capture the main idea and copy the iterations noting multiple or continued (you may copy the entire conversation and please bold the idea)

Note: if an idea is communicated multiple times in a multi-step synthesis step, please capture at each instance.

Note: if any disconfirming ideas appear, please highlight in red

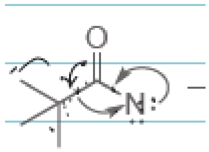
Note: if any prompts are used to get participants to explicitly state something, please copy the prompt in the note and highlight the prompt in "neutral" orange.

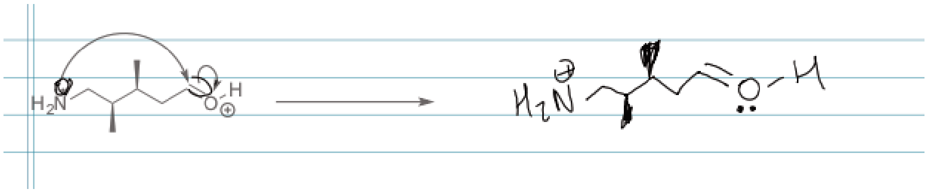
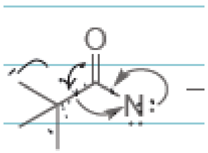
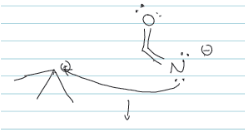
Questions were ordered from 1-72 where 12 participants had 6 questions. 7 Interview questions (~10%) were randomly selected through Microsoft Excel's "=randbetween(1,72)" function and attached as a package for inter-rater review. The package includes this document, a PDF of the question including the audio and drawings; and a transcript of the question. The interrater review had a percent agreement of 83.07% and a Krippendorf Alpha of 99.79%.

Ethics

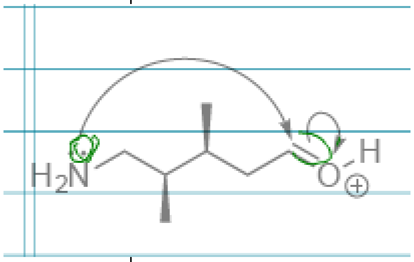
At the **University of Ottawa, 13 participants** were recruited by email that were enrolled in Organic Chemistry I during the **Winter 2017** semester. All participation was voluntary, and participants received a $10 Starbucks or Tim Hortons gift card as compensation. We have also received Ethics approval under the **REB File #: H11-14-09.** In order to keep and protect participants confidentiality, all names were changed to pseudonyms.

Lewis Structure Normative			
Code	**Definition**	**Example**	**Image**
Positive as lacking electrons	Indicating a positive charge as lacking electrons	[00:21:47.04] Zoe: Because, because this is **a positive charge, it doesn't have the electrons**	N/A
Negative as excess electrons	Indicating a negative charge as extra electrons	…so if this is positive then it's missing **electrons and if this is negative, has too many [00:31:43.24] Layla: Like more than the usual I guess**	N/A
Partial Charge	Capturing any instance where partial charge is brought up	Mason: so like here, to use an example we have two electronegative atoms which are both, both have charges, **but here we have like a partial charge on** a non electronegative atom, like carbon is a very neutral atom, so having a charge on carbon is kind of frowned upon usually, because it’s unstable which I guess just a way of saying, not supposed to happen.	N/A

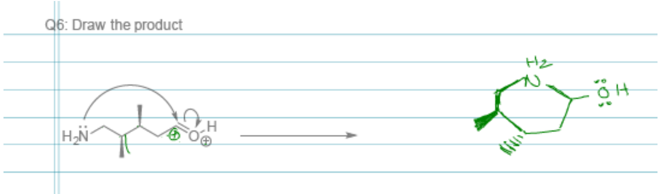
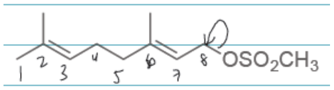
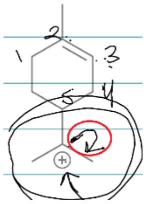
Lewis Structure Interpretations			
Code	**Definition**	**Example**	**Image**
neutral areas of a molecule are inactive	Indicating that neutral areas of the molecule are inactive	[00:51:24.27] Layla: Um I was going to draw like this part just because I thought **like it would be pretty simple, right just because I already have, like nothing's happening really at the end here[00:51:39.15] Layla: This carbon has like, yeah I don't I know I guess I can call it no charge either, so I guess like you wouldn't really want to touch it**	Reference to carbon t-butyl 
Charged areas of a molecule are reactive	Describing charges/charged areas of the molecule to be the reactive point	Liam:uh, it depends on what you have, uh sometimes if you-- you read the whole question and you see **Liam:uh, it depends on what you have, uh**	Image below

		sometimes if you-- you read the whole question and you see the cha-- charge it means--it shows that you've lost something or gained electrons of some sort, and then... you know what reacted with what and it can help you continue you're problem solving thinking of some sort, and then... you know what reacted with what and it can help you continue you're problem solving thinking	
			
Neutral species are final products	Indicating neutral species are final products	[00:51:39.15] Layla: This carbon has like, yeah I don't I know I guess **I can call it no charge either, so I guess like you wouldn't really want to touch it** (reference to t-butyl carbon)	
Charged species are intermediates or reactants	Indicating charged species are not products	[00:40:10:15]Lucas: There's um, like this is left positive, this is left **negative and it makes it seem much more like an intermediate…than a product**	
Make all reagents neutral	participant's goal is to neutralize all species. (Get rid of charge, neutralize)	[00:50:06:29]Lucas: I would say that the uh chlorine is going to uh want to take this uh bond, no not this bond sorry, this uh electron pair and then bond to a nitrogen to create (...drawing) oxygen, NH, that's a (terrible H?) so that would be NH (...drawing) ah that's supposed to be chlorine. **Because this**	Image below

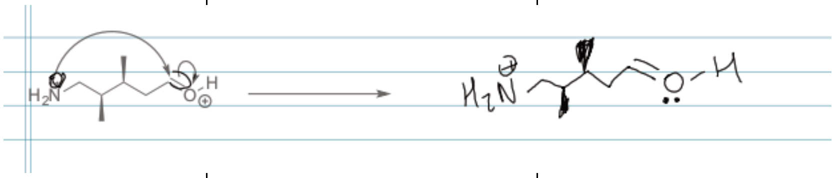
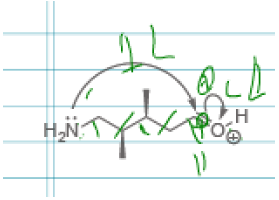
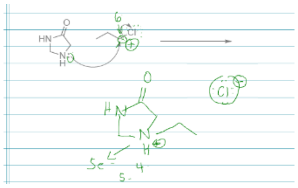
		way everything is neutral now, 'cause the nitrogen has one, two, three, four, five bonds coming off of it so it's happy.	
			
Charge is important	Answering the question to How important is charge. (indicating charge as important, required, or provides information on how to use charge to solve the problem) (if prompted add a * to the start of the example, as well as include the prompt)	[00:46:26:05]Lucas: Um, **again charge was everything,** which I think is why I wasn't getting the uh, the uh cycloheane one because I think I might've had to think of it outside of charge and I'm pretty bad at that	N/A
Charges as Objects	Giving charge physical characteristics (leave, go away, disappear, anthropomorphism)	[00:35:15:]Liam: So once it fills out his octet, right now it's not full there is only six electrons so it's a positive charge, it has lost electron. So this, to be happy it has to have eight electrons attached to it somehow. **So you have to move, add electrons to make it happy, remove the charge but then central carbon atom is not happy so it has to take electrons from somewhere else.**	Image below

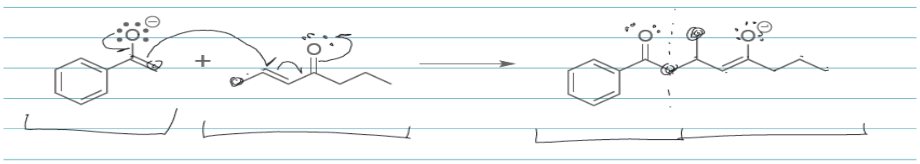
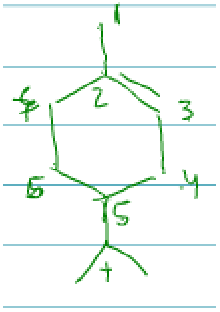
			
Submicroscopic Zoom in.	Answering the question to the "zoom in" (more details on "zoom in" will be in the Word document) “how do you picture this happening in your head)” “how do you see the reaction occurring if you zoom in really close with a microscope” “Why do you think this reaction will occur if you poured these two things in a flask. Why do you think that would be the product you get? Just hypothesize for me.”	[00:07:49.28] Interviewer: Yeah, um great um uh just see here. So when you're, uh when there's a step that has more than one arrow, I guess, each of these types has two arrows, two curved arrows, um do you, if you're picturing this happening in your mind or like in a flask or something does, does um the order of the arrows make a difference? Does one arrow happen before another or do they happen at the same time?	[00:08:22.06] Zoe: I think I usually go, okay well I always go with like, internally in one molecule, so like if it's, if it's two molecules [00:08:30.26] Zoe: Like this one going to this one, this one I usually make last happen, so if it's happening within the molecule, these would occur first. So like, I don't know how to explain, like this, this step would occur first before this step, because it's happening between two different molecules [00:08:44.24] Zoe: Okay, yeah that's, that's generally how I do it. If it's like within one molecule, I usually just kind of go with whichever one, it doesn't really matter to me

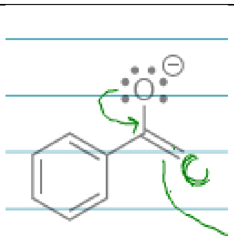
Electron-pushing formalism Normative			
Code	Definition	Example	Image
Source to Sink	Electrons move from a source of high electron density to a sink of low electron density	[00:40:34.25] Zoe: Okay well the charge on the oxygen showed **me that it was going to be the carbon- uh the carbon- the electron uh sink, so** it was going to be receiving the electrons from somewhere, which is why that double bond was broken in the first place led to the carbon having a positive charge uh afterwards	Image below

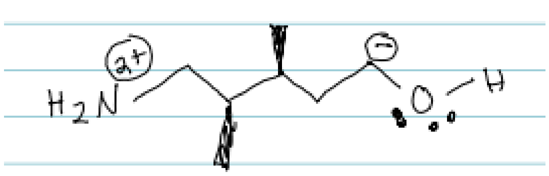
<table>
<tr><td></td><td>(negative to positive)</td><td></td><td></td></tr>
<tr><td colspan="4"> </td></tr>
<tr><td>Curved arrows</td><td>Curved arrows depict electron movement (not atom movement)</td><td colspan="2">Mia:<i>“There’s an arrow</i> [Arrow 1] <i>from the bond um the bond to the oxygen atom which means that this bond [Oxygen-Hydrogen] is going to be broken and the electrons are going to go to the oxygen”</i>
 </td></tr>
<tr><td>Reverse or illogical</td><td>Visually showing arrows are drawn in reverse or illogical. Reverse arrows are starting from an electron source, and pointing to an electron sink. Illogical arrows are arrows that were not correct and not in reverse.</td><td>Example of a reverse arrow
 </td><td>Example of illogical arrows (circled in red)
 </td></tr>
</table>

<table>
<tr><td colspan="4">Electrons as objects - interpretations</td></tr>
<tr><td>Code</td><td>Definition</td><td>Example</td><td>Image</td></tr>
<tr><td>Transplanting electrons</td><td>Picking up and placing electrons
Picking up and placing electrons (Must be visually seen)</td><td>[00:32:48] Liam: So I just moved the electrons, this electron, these electrons moved all the way over to this double bond but I saw this double bond bro- the pi</td><td>Image below</td></tr>
</table>

		bond broke and then added a pair of electrons to the oxygen filling its octet making it happy. Removing his positive charge.	
			
Delocalization	Capturing any delocalization / resonance discussions	[00:34:10] Liam: Changing its position, moving around...[00:34:14] Liam: Since delocalization and localization is just changing its place.	
Stepwise understanding of EPF (sequential)	Interpreting each curved arrow singularly	**Jackson: like it could be the first step then this, or this be the first step then this....Jackson: yeah. Because I don't think it can happen at the same time?...Jackson: because I think that it should be one happens and then it must happen. More of a chain reaction rather than boom. And it's all done**	
Simultaneously (concerted)	interpreting all the curved arrows in a singular step happening simultaneously	Interviewer: okay to recap, does it happen at one time or all at once, or do you think one arrow happens and then the next **Mia: I think it happens all at once, but to make it easier, it would be easier to do it step by step.**	

Mapping Strategies			
Code	**Definition**	**Example**	**Image**
Comparing features in the reactants, intermediates, and products.	Comparing surface features between reactants, intermediates and products	[00:20:55:26]Lucas: So for instance, **here I See that single bond to an electronegative oxygen, and the over here I see it's a double bond to a neutral oxygen a**nd I've seen just many times before in my notes and studying... And assignments and that, that what can happen is the double bond will break and then go to the oxygen, um so that-that's how I just, I believe I started with this, that's why I started there	Image below
			
Mapping	Labeling atoms in reactant and products as a form of accounting	Mia: so this just showing me what happened after that. Ooh. So that means I have to make a bond between some of the carbons inbetween here and I know that it has to be inbetween because there are constituents on the side so that means it's not making a bond from end to end and it looks like lets check. **One two three four five six, so that's *inaudible***	

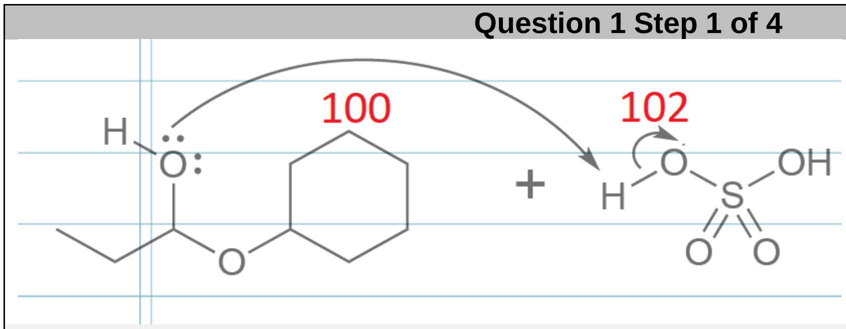
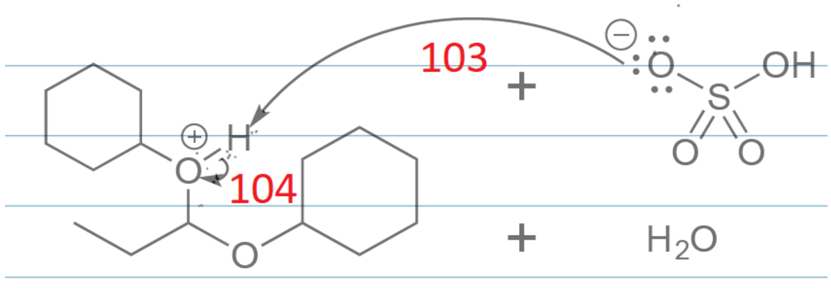
Chemistry Reasoning			
Code	**Definition**	**Example**	**Image**
Octet	Capturing any octet discussions	[00:57:55] Adalyn: I am not sure how to draw it and I don’t know if it happens or not. As for this one um. Um. I want to say an extra hydrogen comes in to fill the octet for nitrogen.	N/A
Determining charge through the number of electrons	Associating the number of electrons on an atom with formal charge (or vice versa)	Aria: I was going to draw something here but, I wasn’t really sure how to move it yet. And I just looked here and **I saw there was a formal charge of negative, so that means there would probably be like three lone pairs on the oxygen** and so that’s going to draw an arrow like, to the oxygen. The double bond there. And then since there is a double bond over here, that probably means that this double bond. The electrons move towards there	

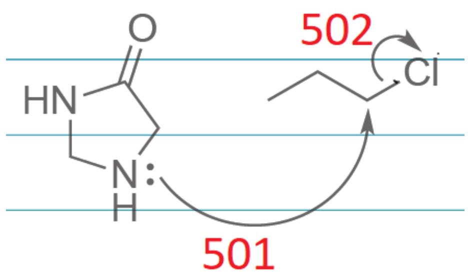
Determining charge through the number of bonds	Associating the number of bonds on an atom with formal charge (or vice versa)	Aria: um. Because **because nitrogen has a regular charge of five and from like here. If you count the bonds,** there's only three. So it would be like five minus three which would be like a two	Image below
			
acid-base	Capturing any acid/base discussion	Nora: Um and then we started doing curved- but we didn't actually really start drawing out mechanisms, like we were doing some very like basic aci- (mumble) (laughs) so we were doing a lot of simple acid base stuff	N/A
Stability of charged species	Discussing stability of charged species (including electronegativity and size)	Adalyn: Well we have one two three four five six then you have a seventh one..the same one. I don't know if the plus charge with the circle around it, I don't know if that's also a thing. Cause you still don't know if that's just the electronegativity thing or just the electron kinda disappearing. Or maybe it's both. I think I would just put a hydrogen here.	N/A

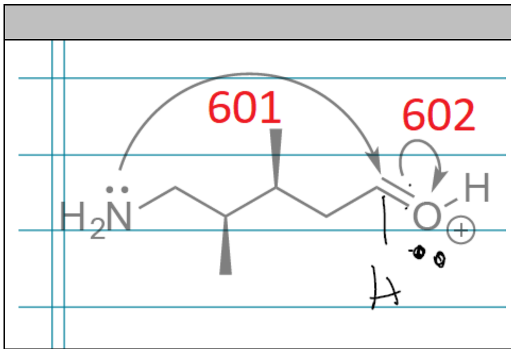
Reaction Occur	Discussing why the participant believes the reaction occurs (if prompted add a * to the start of the example and include the prompt)	[00:58:49.20] Interviewer: Okay, okay um so on the previous one I asked you something similar, so why do you think that this reaction would happen if you could hypothesize for me about why Nora: Um I think that the oxygen is not happy being positive maybe	N/A

Appendix 5: All responses describing EPF arrows as either breaking or forming bonds

Participants discussions of EPF arrows describing a bond-breaking or bond-forming process

Question 1 Step 1 of 4	
	
#01:	***“An electron pair from the oxygen is pointing towards the hydrogens*** *[Arrow 100]* ***so that must mean there’s a, there’s a bond that’s suppose to form between both of them*** *and the bond is supposed to break from this hydrogen, between this hydrogen and this oxygen um the electron is supposed to go to the oxygen.”*
Question 1 step 4 of 4	
	
#01:	***“There’s an arrow*** *[Arrow 104]* ***from the bond um the bond to the oxygen atom which means that this bond is going to be broken and the electrons are going to go to the oxygen*** *so that is why it this Sulphur compound ends up stealing the hydrogen. So when. Lets see um, so.* ***So the electrons*** *[Arrow 103]* ***here goes to pair with the hydrogen****. And the* ***bond between hydrogen and oxygen gets broken*** *[Arrow 106] which is why oxygen gets to keep all the electrons and it no longer has a charge [Molecule 108].”*

Question 5	
	
#02:	*“I don’t see any bonds forming, but breaking here was the bond here from this arrow to this chlorine [Arrow 502]. And yeah. That would have made it. Broken the bond instead of the electrons being on the carbon will be on the chlorine.”*

<table>
<tr><th colspan="2">Question 6</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>Int:</td><td><i>“Okay great. Lets see. Um. I was going to ask about being bonds breaking or being formed here, how did you know. I guess you said you knew electrons were being transferred. What shows you electrons are being transferred?.”</i></td></tr>
<tr><td>#02:</td><td><i>“The arrows”</i></td></tr>
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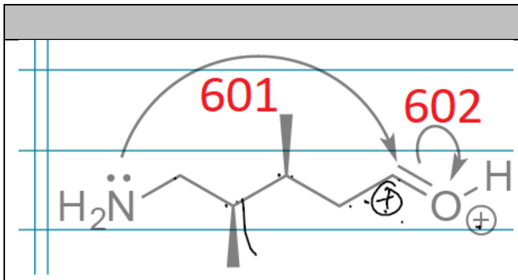
<tr><th colspan="2">Question 6</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>#04:</td><td><i>“This arrow [Arrow 602] indicates that this double bond is being broken because it's pointing towards that actual double bond and it's being, the lone pairs are being given to the oxygen”</i></td></tr>
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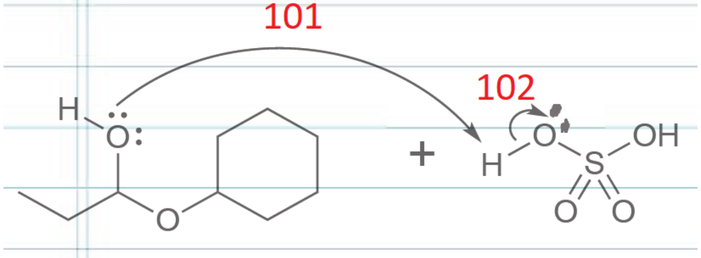
<table>
<tr><th colspan="2">Question 1 step 1 of 4</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>#05:</td><td><i>“Yeah, so it's giving it's electrons here to the hydrogen [Arrow 101] and then I guess, I have no idea how they got to this step, or I guess they're adding it? I don't know, seems kind of weird to me, I'm not sure what this is Um (...) okay so I guess that this arrow [Arrow 102] means that they're taking some sort of bond out”</i></td></tr>
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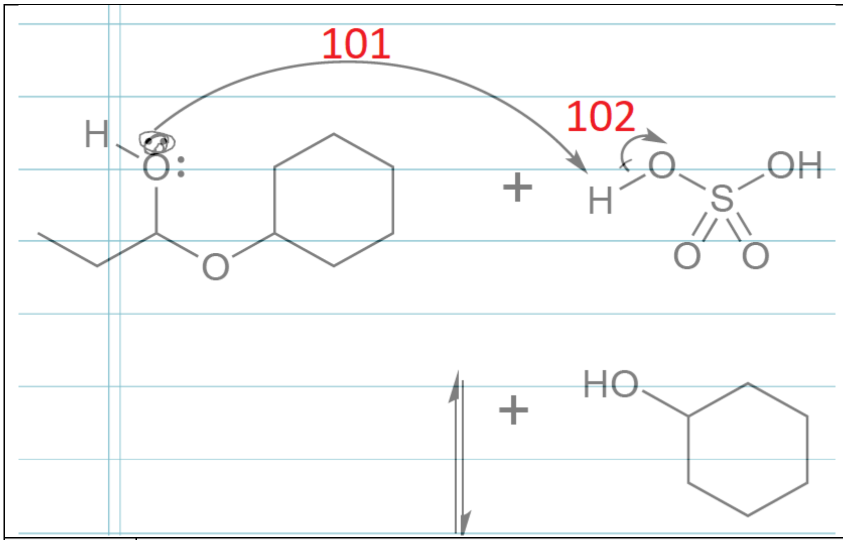
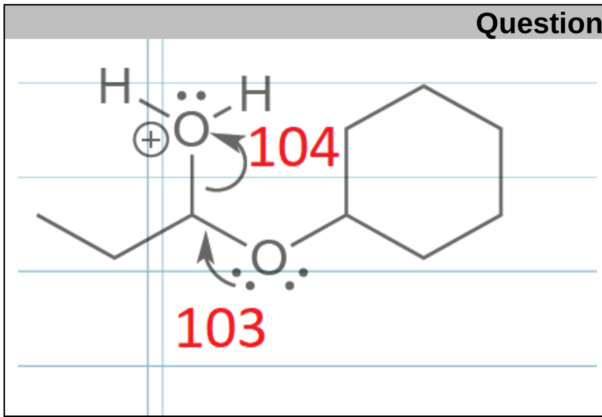
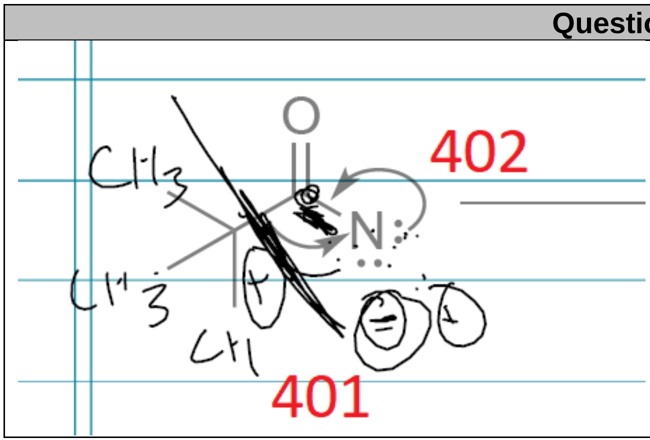
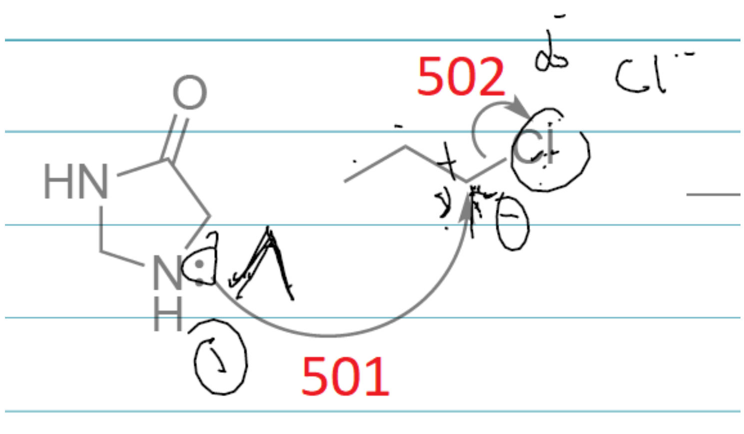
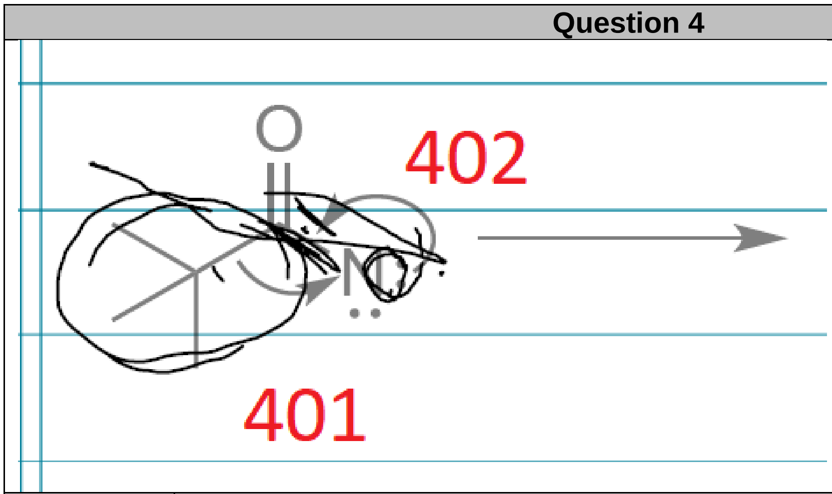
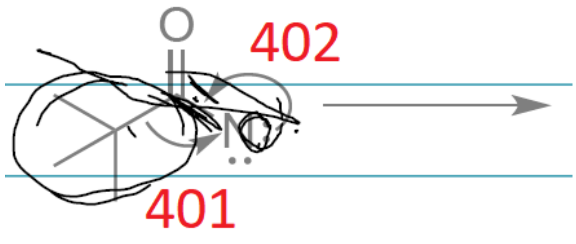
	
#06	*“Um because you can see here the uh bond […] Was broken and those two electrons that were here uh, one from the hydrogen went to the oxygen as indicated by that arrow [Arrow 102].”*

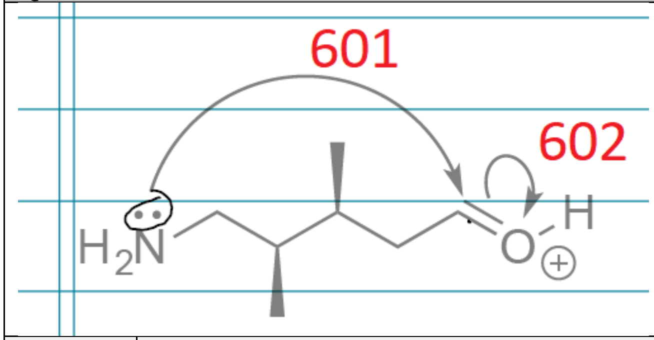
Question 1 step 1 of 4	
	
#07:	*“The bottom one [Arrow 103] shows that the electrons are creating a bond with the next-- the carbon, the central carbon atom and then that's [sic] carbon atom is, also breaking the bonds [Arrow 104] so that re--releases water, releases water in the next -- in the next step, I suppose.”*

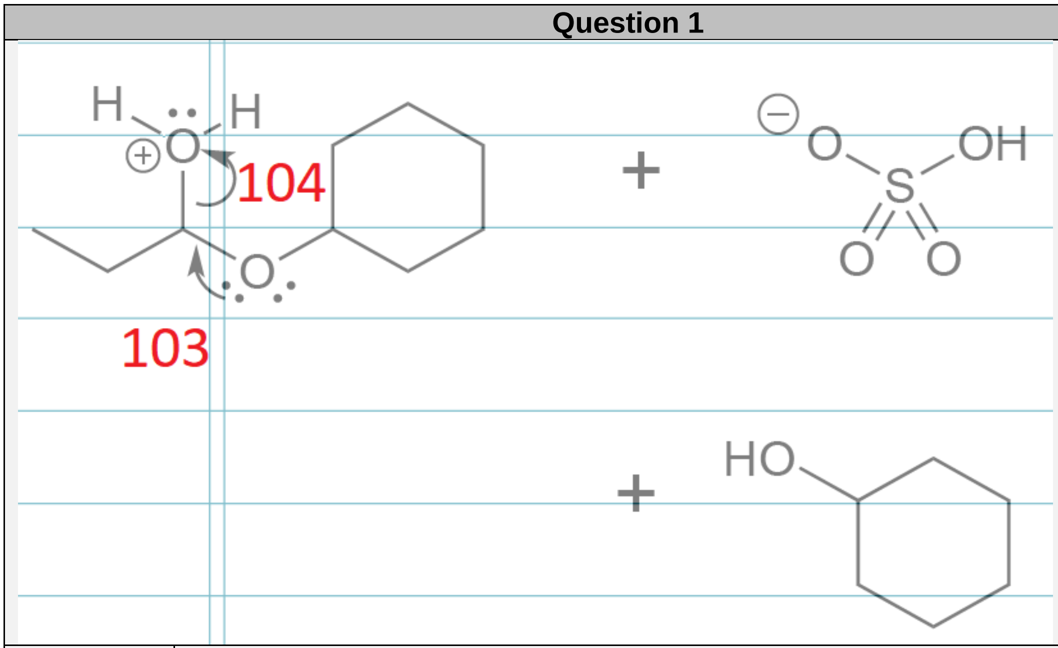
Question 4


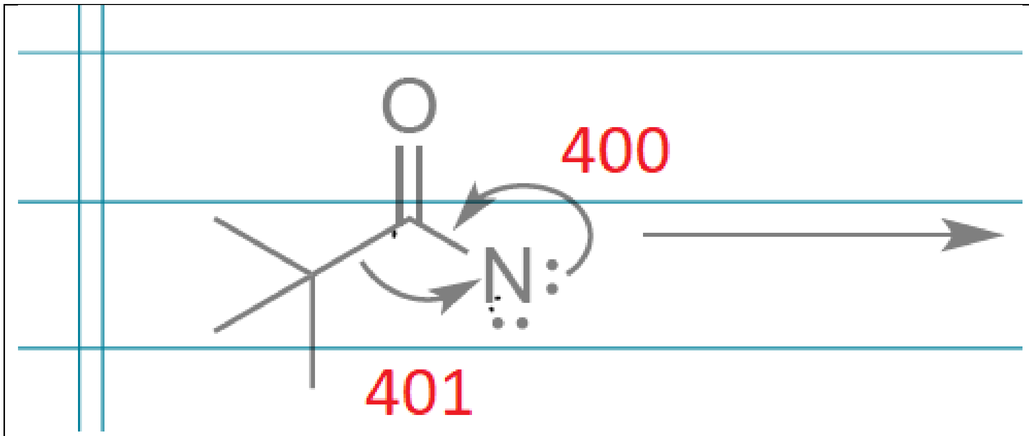
#08:	*“So here first off I guess we should look at this bottom arrow [arrow 4015. Which is actually breaking a bond here.”*
Question 5	
	
#08:	*“I look at the things breaking bonds first so this would make a CL minus because we’re taking, looking at the direction of the arrow [Arrow 502], we’re taking electrons out of this bond and making a lone pair on the CL like on the chlorine.”*

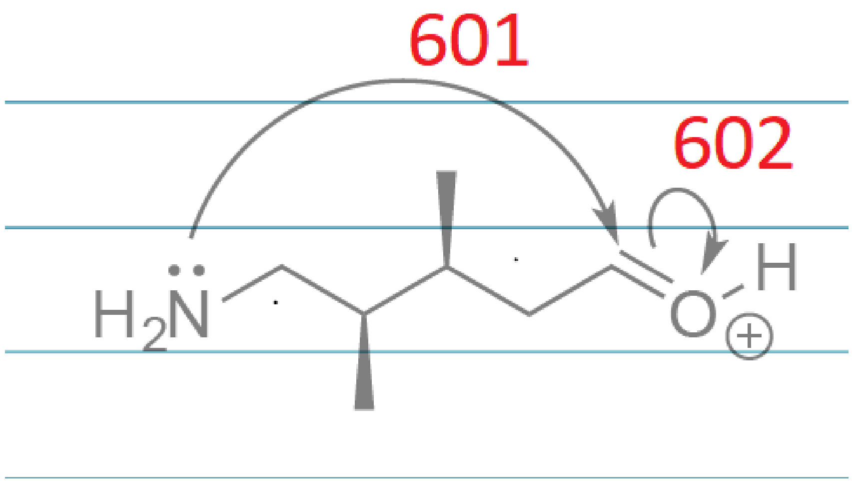
Question 4	
	
Int:	*What does the arrow [Arrow 402] show you?*
#09:	*It shows me that a bond is forming, or the electrons are moving*

Question 4	
	

#11:	*“Well there is an arrow pointing from a lone pair to a single carbon nitrogen bond and there is a carbon carbon single pointing to the nitrogen. […] Um, I think one bond is being broken and one is being formed.”*
Question 6	
	
#11:	*“So there, already that has three bonds, so this pair of electrons I'm assuming is, it wants to go away so that's why it's leaving via the curved arrows [Arrow 601], you can see, so then it's going to that carbon There's a double bond that's leaving and this arrow[Arrow 602] is pointing towards this, this atom.”*

Question 1	
	
#12:	*“Um and then you have an arrow [Arrow 103] from the other lone pairs going onto the bond so you get a double bond between the carbon and the oxygen.”*
Question 4	

	
#12:	*“The back of the arrow's [Arrow 401] on the bond and the arrow head is on the nitrogen, it means that the um, well the electrons are moving on to the hydrogen [sic][Nitrogen], not between the carbon and the nitrogen because if you look at the arrow [Arrow 400] um that's showing you the electrons onto th- like to the bond […] Um it's showing it to the bond so it means it's between them […] Um, so that's how I knew that it was um a lone pair and not a bond, like another bond between then carbon and nitrogen.”*

Question 1	
Int:	*“So how do you know that the the bond that's breaking is giving its electrons to the nitrogen?”*
#13:	*“Um because arrows are usually drawn to show the flow of electrons from one place to another […] So if it starts in the bond then the electrons are being taken from the bond and given to wherever the arrow was pointing.”*
Question 6	
	
#13:	*“But I also see an arrow which is forming from this onto here, so um which means that this double bond is being broken and it's giving oxygen a lone pair”*

Appendix 6: All responses comparing product and reactants to determine EPF arrows for question 2

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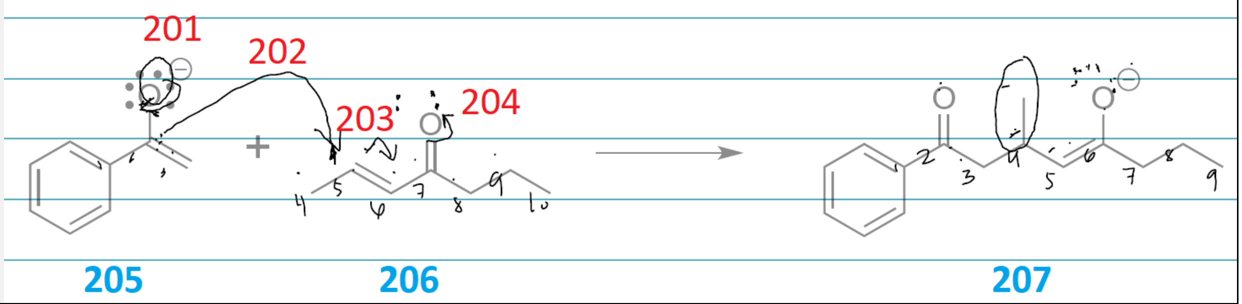
<tr><th colspan="2">Question 2</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>#01:</td><td><i>“I’m looking at the product and I’m seeing where the bond is supposed to form […] And then I have to figure out which electrons move to make which bonds, so from here it looks like um because there’s a charge here and there’s no charge on this um the product um I’m going to move the pair of electrons to make a double bond the oxygen and the carbon [Arrow 201] that means that this moves here but there’s no double bond here and there’s a double bond here so that means one of bonds here has to break […]”</i></td></tr>
<tr><td>Int:</td><td><i>“Talk to me about why you decided to work through the problem in that way and how that helped you to be able to know where to draw the arrows.”</i></td></tr>
<tr><td>#01:</td><td><i>“I think it was mainly because I was looking at the products so it was easier to know how the bonds were going to move um to form the compound and then I did um minor so little ones before little changes to each compound before I connected them, so I decided one on one side, and I looked at the product and then what changes I could make on the second molecule and then I saw okay how can I put both molecules together and then I saw this how it looks like in the product then it has to make a connection the first one the first one has to make a bond with the second one through this carbon.”</i></td></tr>
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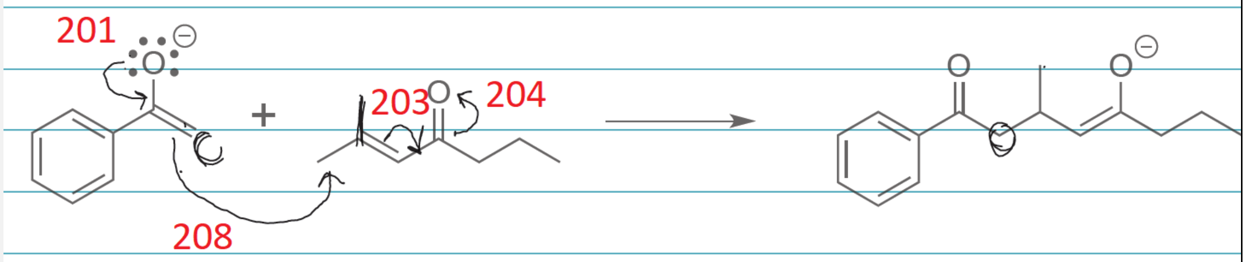
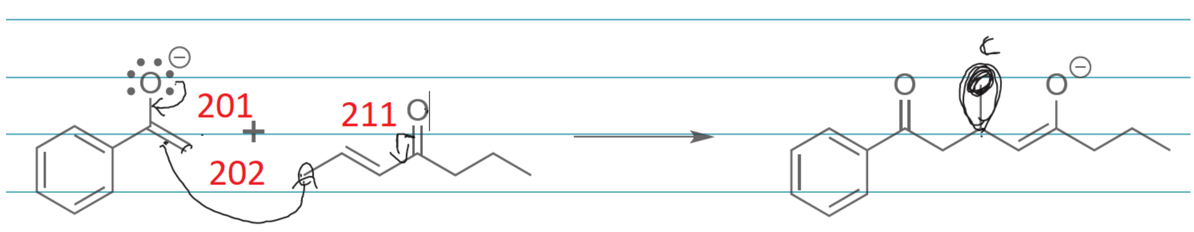
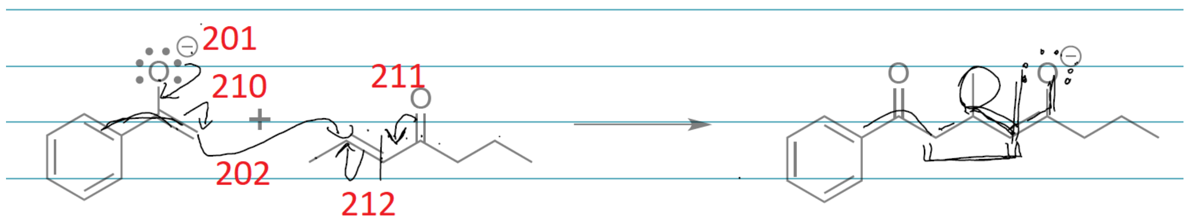
<tr><td colspan="2">
</td></tr>
<tr><td>#02:</td><td><i>“I just looked here and I saw there was a formal charge of negative, so that means there would probably be like three lone pairs on the oxygen and so that’s going to draw an arrow like, to the oxygen. The double bond there. And then since there is a double bond over here, that probably means that this double bond. The electrons move towards there.”</i></td></tr>
</table>

Question 2



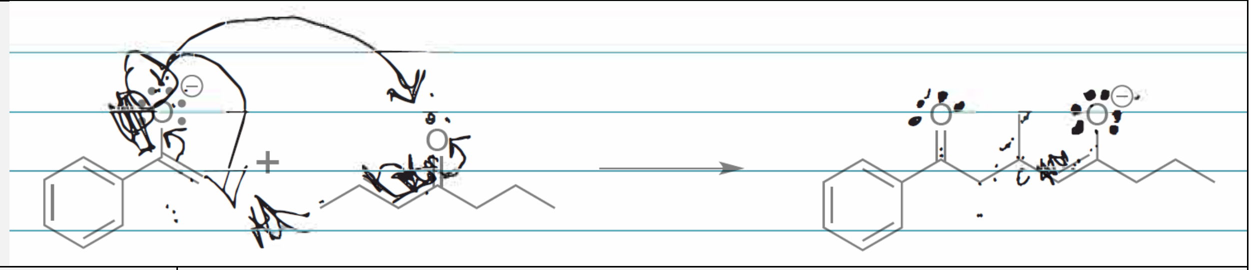
#03:	*"okay so. I can see that here is a negative charge on the oxygen. So I have to figure out a way to put a negative charge on that guy. And he is a negative charge now. And these two are going to attach. So I'm going to move. It would be. Would it be more than one step? Or is just one step? […] so the double bond here. I'm moving it straight to the bond there to make that a double bond, instead of showing it in two steps, I'm just doing it in one arrow."*

Question 2



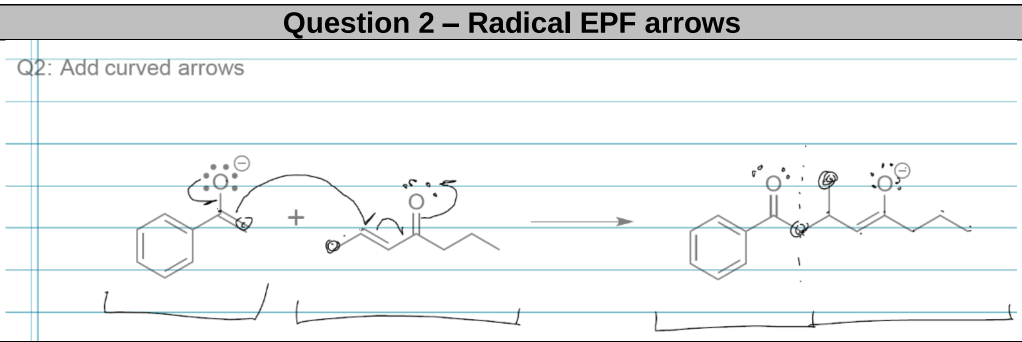
#04:	*"Okay, okay um so hold on, okay this part of the molecule over here would be this part, I think, wait yeah about like this part […] This part over here so because this is an electron source, we need a sink somewhere […] So uh and this one has a negative charge, so it must have a bond somewhere, so this- oh okay so this is a single bond, so it would go back to this state, leave"* *"Oh, because here, uh here there was a- there's a single bond"* *"With the oxygen, and here whe- there was a double bond so that means the electron- oh and there's a double bond over here so that means the electron group must've moved over here instead to create that double bond, leaving it with a negative charge"*

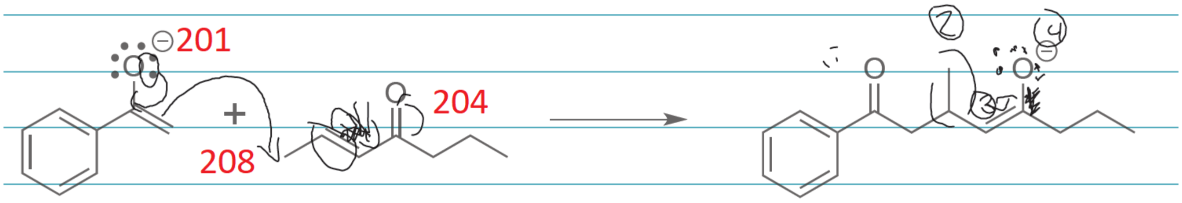
Question 2



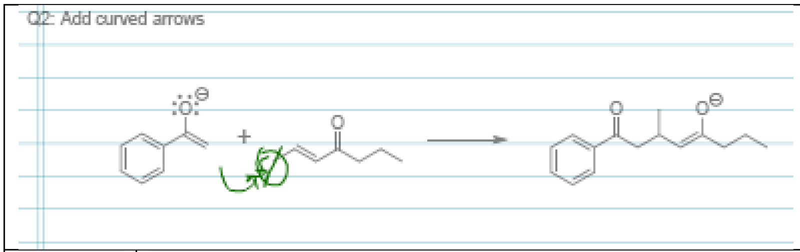
#05:	*"Okay, so okay so I guess like one of these pairs of electrons um would come (...drawing) wait so this is like, easier if you like broke it up and put it like this one […] And then you want to put it together okay so I think may- oh so I think this pair of electrons here would make a double bond there […] And then um so this one here I guess, one double bond came here and then so this- one, two."*
Int:	*"What are you counting?"*

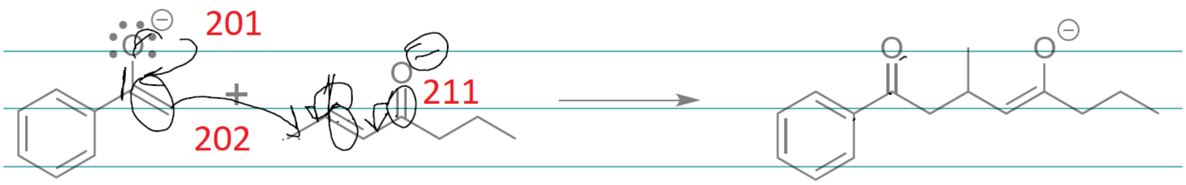
#05:	*"The b- the number of bonds so, okay so here there's one, two, three, four […] So I guess this one would then have four to the- (...drawing) so then maybe I guess I need a minute like […] I just want to see like what I've done so far […]And how it kind of matches there […] (...drawing) so I think, yeah so like this part matches now […] And then, so there's a double bond here that shouldn't be there, and like you want this coming up so maybe it's just transferred up […] I don't know if you can even do that but (laughs) maybe, not sure what else you would do with it, so, I want to say that's what happens"*

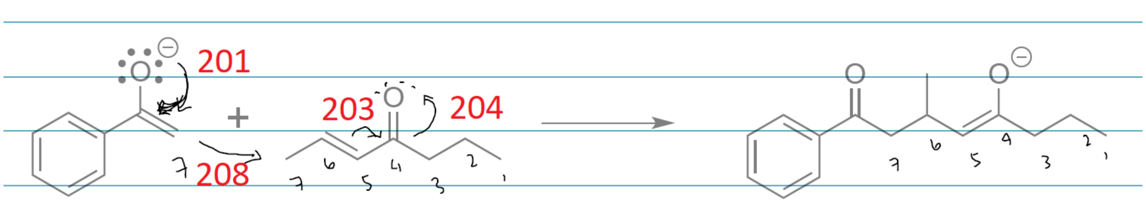
Question 2 – Radical EPF arrows	
	
#06:	*"So first is see where the separation is um […] Between them, just to kinda see where each one is in the final product."*
Int:	*"For your arrows you have it, only on one side of the line instead of on both sides here."*
#06:	*"Well that's just um uh, that's just 'cause I'm lazy […] Um also on sapling, when we do it on sapling […] So, it doesn't really matter when I do […] Drawing arrows sometimes in my notes I do the one sided, sometimes I do the two sided […] Yeah tha- there's no real […] reason to that, it's just **I don't know if there is a difference between them**."*

Question 2	
	
#07:	"I circled the electrons and moved it to the bond to crea-- to remove the negative charge and make it a double bond with the oxygen
Int:	"okay, why did you decide to do that."
#07:	"cause of the neg-- in the products I see there's a double bond made, no charge and the electrons are all gone."
#07:	*"so next I just-- that double bond attached to the oxyg--carbon is, if there's a double bond you can't have the extended [sic] octet so you have to break that double pi bond […] in order to connect--to make another methyl group, here."*

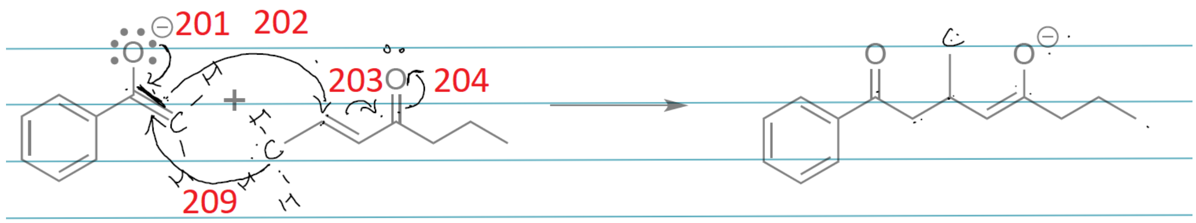
Question 2

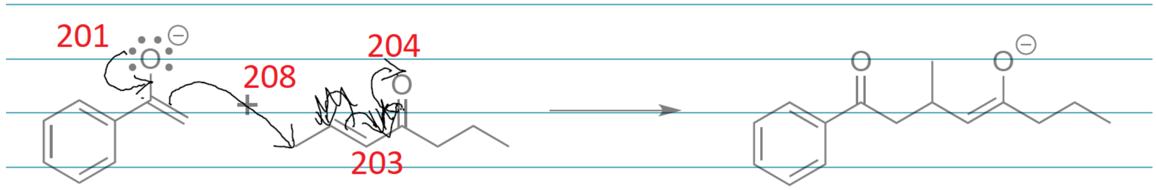
	
#08:	*“oh okay, ah, um well, I guess we’re bonding right there so [tsk sound] […]oh sorry, I was just saying right there […] that's one, two, three, four, and I think that would be the [inaudible] yeah, okay so like, this is the bond we’re making or like the thing we’re putting together […] I was just like making sure, like finding out where it was on here […] like so I knew what joint, I guess, I was actually talking about […] so it would be like trying to bond this.”*

Question 2	
	
#09:	*“Okay, I'm just looking at uh, at how this one became this one […] Um, okay so there's a double bond, […] And then a double bond here, um there's a lot going on here.”*
Int:	*“Okay okay that's fine, if you're not sure um that's okay um tell me about um, when you're trying to decide where to draw the arrows, what are- what's um what helps you decide what to do?”*
#09:	*“Um I like to look at the, the double bonds first […] Um, well I know that a double bond has the capacity to become a bond somewhere else or a pair of electrons, […]Versus like this little carbon, or yeah, I can't really, I guess I could move that but we don't usually move single bonds, they stay where they are, um and then again another indicator would be the negative charge.”*

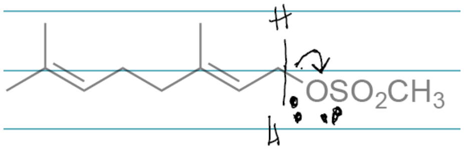
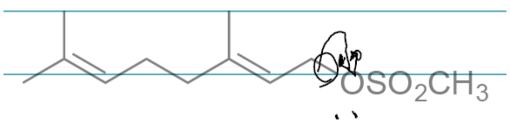
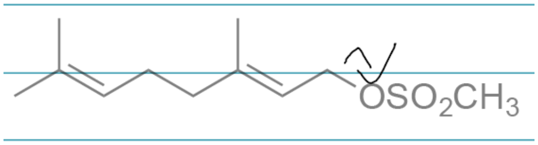
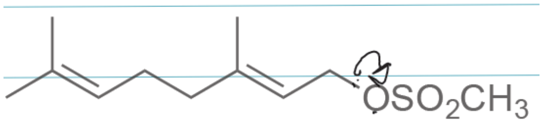
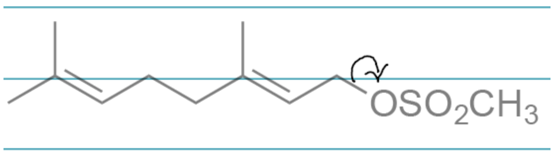
Question 2	
	
Int:	*“What does the labeling tell you?”*
#11:	*“Oh the carbons? […] Um, the position of the car…, into each individual carbon […] So, one of the double bonds is broke into a single, um. [Pause] I think there would be an arrow leaving to the negative.”*

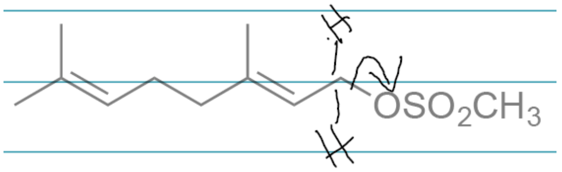
Question 2

	
Int:	*“So when you're working through a problem like this, talk to me about how you decide where to draw your arrow, how do you know where it's going to start from and where it's going to end.”*
#12:	*“Um, well if you're given the product I find it's easier because, um once again I just look at the charges, which is like where I kind of start off my um, my thought process. So like right away I saw that the um oxygen does not have a charge uh in the product and I also saw that it has a double bond so um from that I knew right away that you have to move um one of the lone pairs down to form a double bond um and then same thing here, I saw that there was a charge and um in the reactants there was a double bond. Um so I knew that I had to move one of the bonds up to form a lone pair.”*

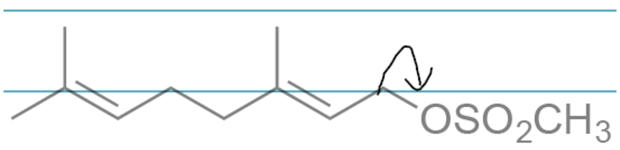
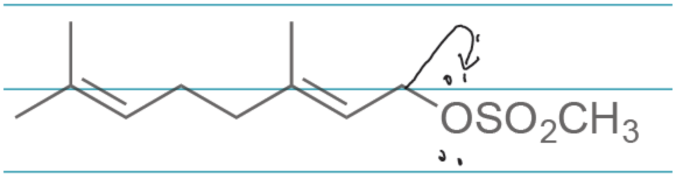
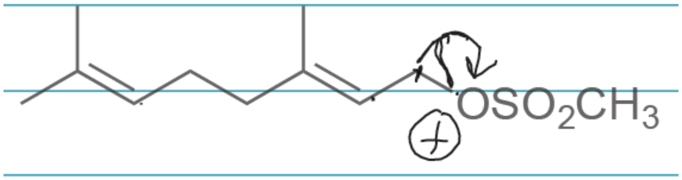
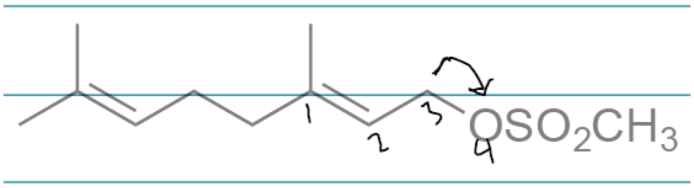
Question	
	
#13:	*“Okay, um well first I think that, well we see here that there is a double bond, this makes it ketone so we need electrons to go into this bond and I think that the […] Only source would be this oxygen […] That has a negative charge, so I'm going to draw an arrow from the, these electrons to this bond, and then the next thing I see is that there is (...) um okay so this would not, there would not be a double bond here if we're looking at, like if we smushed these together (laughs) so I'm- and we need a bond from here to here somehow, so I'm going to put electrons from here, this double bond onto this carbon.”*

Appendix 7: All responses containing the correct EPF arrow (301) for question 3 step 1 of 3

Participant #	Question 3 step 1 of 3 - Carbon-carbon bond to Oxygen atom EPF arrow
#02	
#02	*"Okay so this bond would be broken. Over here. So you can form your two things. I think. So from the bond, the electrons would go to the. Would become a lone pair on the oxygen."*
#03	
#03	*"This bond here is broken. Like it doesn't exist anymore, which gives that carbon a positive charge. So that basically this bond is just go to the oxygen here for this step. from looking here. This positive charge tells me there is only three bonds on the carbon. So this bond half and that negative charge shows me three lone pairs so that this bond has to break to give oxygen three lone pairs and carbon those three single bonds, to give it these two respective charges."*
07	
#07	*"So I see in the second step that the I guess I don't know how to name that but […] O compound is oxygen has I guess broken his bond with the carbon atom on the left. It could [inaudible] a charge 'cause it's just hanging around with nothing around it, so it is the bond is broken and that just splits into two different compounds now."*
#08	
#08	*"Okay um, well this one seems kind of simpler a little bit simpler than the last one or maybe I was just. Inaudible. But this negative shows at the electrons of this bond moves to this "O" so moving these electrons and breaking these bond and moving the electrons to the "O" gives the carbon here a positive charge, like where the electrons would be if one had been broken. And there's an extra lone pair on this oxygen, and that's what gives a negative charge."*
#12	

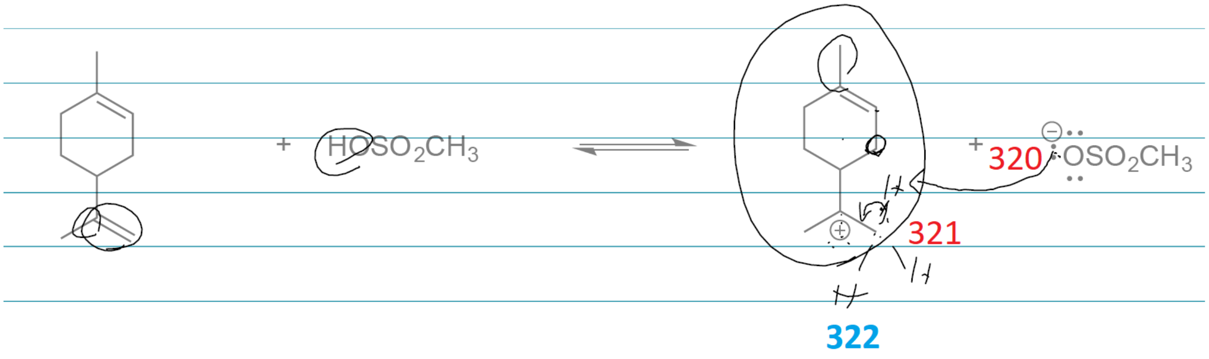
#12	*“Okay, um. So from the products in the first part, I see that the molecule is like now two parts. […] So, um I knew that, I know that like somewhere a bond has to break, […] um and so there's a negative charge on the oxygen so once again you have an extra lone pair on the oxygen. […]Um and there's a positive charge on this carbon, which means it's missing an electron um so you just have um the first bond move on to the oxygen, or the electrons from the first bond to the oxygen, um and then in the second part um you react that with something else. Um, and you form (...) um a new molecule. So in this case.”*
#13	
#13	*“Sure, um okay so nothing is really changing over here, I would, okay so I can see that this ends up being positive, like this carbon at the end […] And this oxygen ends up being negative, um or well the ion ends up being negative […] So, I would move the first, I'm gonna draw the first arrow as the flow of electrons from this bond onto here”*

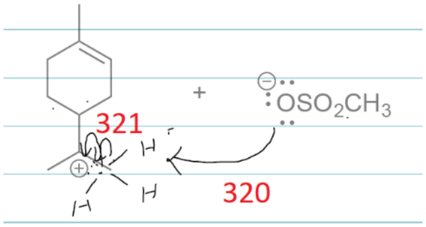
Appendix 8: All responses containing a plausible EPF arrow (302) for question 3 Step 1 of 3

Participant #	Question 3 step 1 of 3 - carbon atom to oxygen EPF arrow
#04	
#04	*"Okay, okay so because it becomes two molecules and it has the oxygen over here that means one of the bonds must've broken in the f- the what's it- the first compound […] So the bond between the oxygen and the carbon is broken, so this one has- because oxygen is more electronegative it's going to take all the electrons from the carbon […] So both electrons would go onto the oxygen which would leave this formal char- the carbon with the, with three bonds, because it has two hydrogens on it, and then attached to other carbon."*
#06	
#06	*"Sure okay, uh so OS, O2, CH3, that's a negative, that's a positive, so to start off, to get this carbon electropositive, I'm going to, yeah this- this oxygen here um yeah, I'm gonna- I'm going to say this one should have the two valence electrons like that So um to start off I'm going to have it move like this […] Uh yeah this bond is uh moving here to give this, uh the three valence pairs […] So now it's an electropositive carbon."*
#09	
#09	*"Okay so this is all the same from here to here […] This molecule moves and then this basically becomes positive, um not sure how to represent that with a curved arrow, a whole molecule coming off."*
#11	
#11	*"I guess there is a-a bond being broken, um for the first step. Um [pause] because of the negative and positive charges in the product […] And how they are kind of at the end of where they would-used to be joined. […] Let's say because you break the bond the electrons goes from where you put 3 to 4. That*

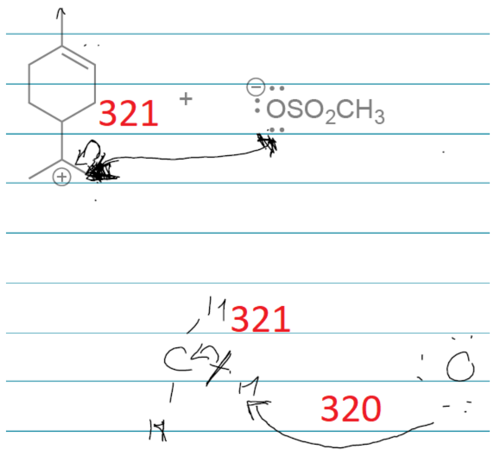
	would cause, hum, since you lose an electron that would cause a positive charge here, and then since it's- the oxygen here, the whole oxygen thingy is gaining an extra electron to have the negative."

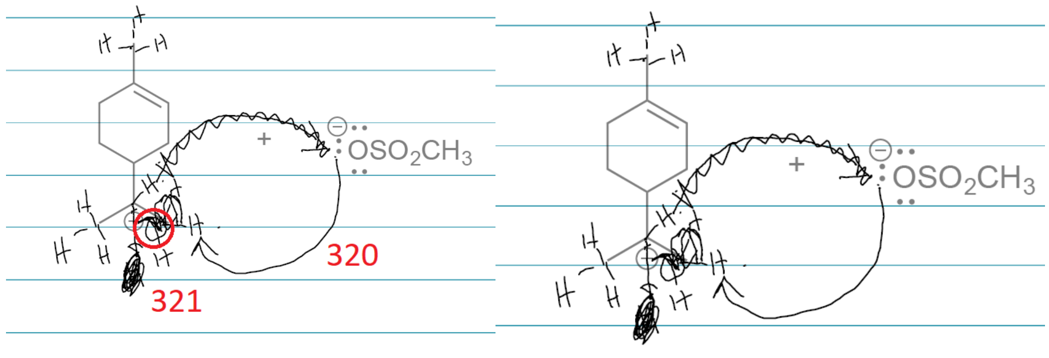
Appendix 9: All responses comparing charges to determine how to draw the EPF arrows for question 3 Step 3 of 3

Participant #03 : Question 3 Step 3 of 3 reading right to left	
	
#03:	"I've got that positive charge on the carbon. So that positive charge tells me that […] it just have three bonds, so it wants to form another bond, um so it has a positive charge it wants to bring in electrons. So it's going to take it's. […] um so. **Because I have to form this double bond here right**. **So I have to figure out a way to take, to take a hydrogen from here**. So I'm going to give away hydrogen […] because all these carbons should for example. Since this guy has no charge he should have technically one two three hydrogens on it. **So if I take one of the hydrogens. Wait so. I'm going to break that bond and give it there**. **And have a double bond there, and take these to form the "O" and the "H" to give us this** [arrow 302]. And then that double bond that was between the double bond and the "H" and **hydrogen would break to form a double bond here** [arrow 321]. To make that carbon neutral."

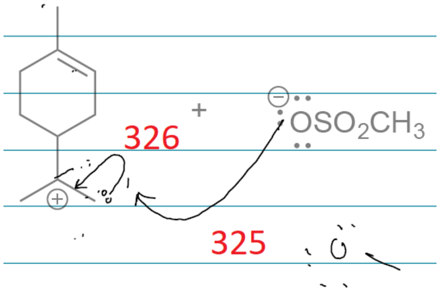
Participant #04 - Correct EPF arrows (320 and 321)	
	
#04:	"Okay so here it gained a hydrogen and the mole- this molecule, the left molecule lost its formal charge because it created a double bond, so (...) hm okay so it, it probably took the hydrogen from this carbon […] Okay, okay so here it gained a hydrogen and the mole- this molecule, the left molecule lost its formal charge because it created a double bond, so (...) hm okay so it, it probably took the hydrogen from this carbon […] So I'm going to assume it probably ta- took it from that which is why the carbon was able to create a, a double bond with the second carbon […] Because uh the- this carbon wo- would've had at least like three hydrogens […] well I assume like this- the electronegativity at least of the uh oxygen when it came closer, it probably pushed these electrons back towards the carbon […] So something like that, which would've created this double bond and the

	hydrogen ion would've been left, which would- which would've been positive and that would uh lead to this bond.”

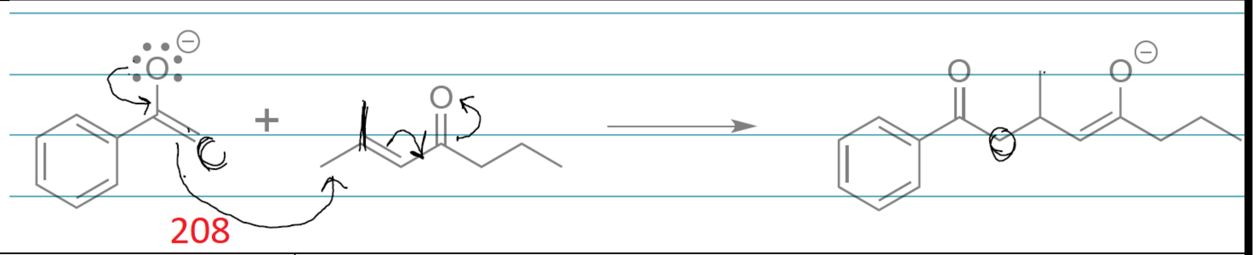
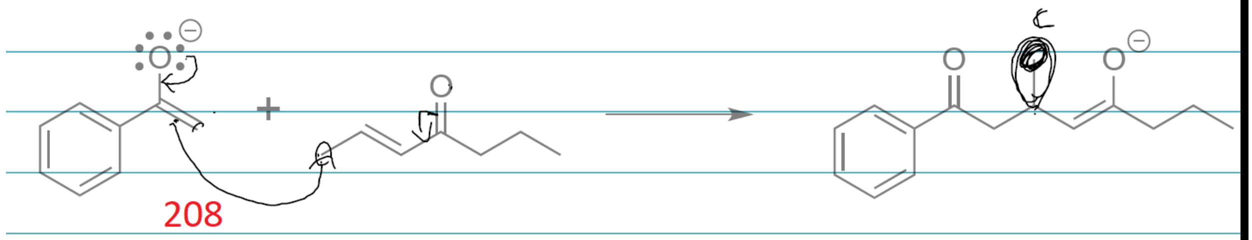
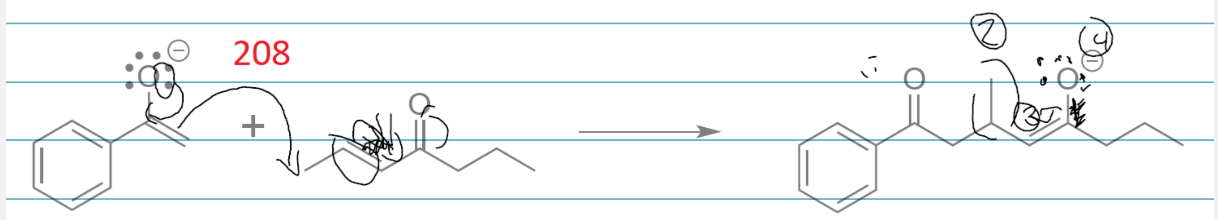
Participant #12 – Plausible EPF arrows (322)	
	
#12:	*“So once again you've got the negative and then positive charges and in your products um you don't […] And you have a double bond um between these two carbons […] So you just have an electron pair, um that moves um from the oxygen that has a negative charge onto (...drawing) that bond. Um […] it takes a hyr- the oxygen takes away a hydrogen[…] And then um the carbon is left with the electron pairs. But then since that would give it um a negative charge, um it forms a double bond with the other carbon.”*
Int:	*“Could you show how that happens? Or do you think that shows it, sorry if that's.”*
#12:	*“Um well I think like since you're showing the electrons. Um actually no, because it would make more sense to show that the hydrogen is being taken, because then you'd have a bond formed.”*
Int:	*“Okay so you flipped that arrow around?”*
#12:	*“Yes […] Um because it's taking the hydrogen [arrow 320], which means it would form a bond, um between, um the (...) so what happens is, like you have your carbons with your three hydrogens […] And you have your oxygen with your um three sets of lone pairs […] So um this bond is broken […] And you end up with the, the hydrogen um moving, or like the lone pairs connect with the hydrogen um to form a bond, and then the electrons from this bond move onto the carbon [arrow 322] […] But then, um since that gives it a negative charge, it forms a double bond.”*

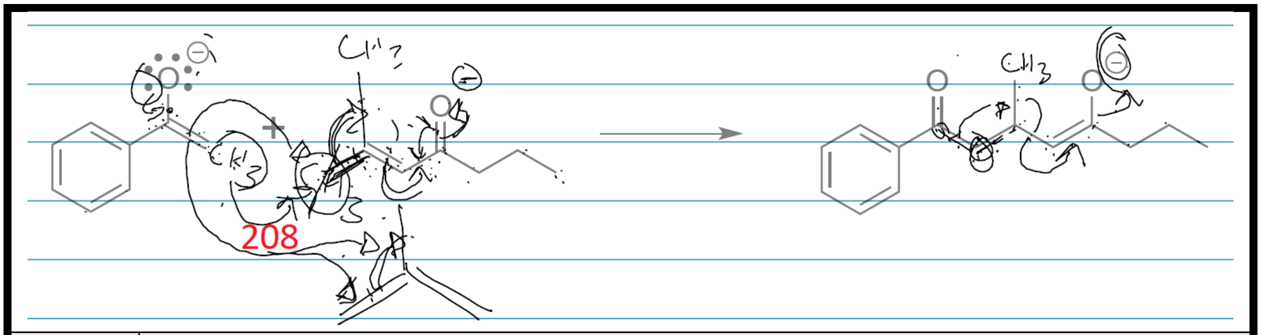
Left side researcher marking - Right side original drawing	
	
#13:	*“I can see here that there's gonna be a hydrogen that um joins with this oxygen on the end here […] And because this no longer is negative when you get to here and there's a hydrogen there, so I'm just gonna draw the hydrogens on this structure just so I can see it*

	[…] ***one of the hydrogens has to go to here because this is no longer positive so clearly the hydrogen has to leave this one*** *[...] And I think one of the, and there's a bond, a double bond now on this side* ***so I think one of these hydrogen bonds has to break because it would no longer be room for that many hydrogens*** *[…] So from this molecule w- I mean from* ***this methyl one's gonna have to go onto the carbon and then those electrons are going to have to go into the bond*** *[arrow 321] […]* ***Which would form the double bond over here.*** *[…] the hydrogen that the bond breaks here with […] Would have to go somewhere, and I think that these electrons from this oxygen are gonna go to that hydrogen [arrow 320] […] So not this hydrogen is no longer on the end carbon.”*

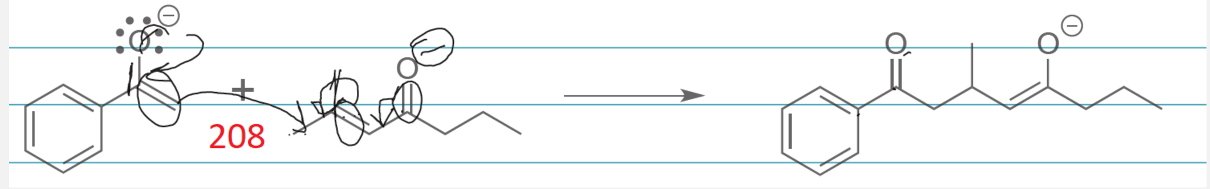
Participant #06 - Plausible EPF arrows	
	
#06:	*“Uh yeah yeah sure, sure so that's OH, okay so looks, it seems as though, this is a hydrogen coming off of it (...) hmm, kay that's says hydrogen coming off of it, this has three hydrogens (...) so (...) so um again this seems like one of these, this lone pair here is gonna take a hydrogen […] Just to, to deprotonate something […] Uh, because this here is neutral, so it se- it would be happy with just the hydrogen so I'm trying to, right now, decide where the hydrogen get's taken from, and then after a hydrogen gets taken that means there's a lone- okay so um, okay yeah so um this this here is going to come and take one of the hydrogens […] And now this carbon has a lone pair on it, meaning it's more electronegative than it wants to be and this carbon here is electropositive, so that means that lone pair that lone pair that was formed here is going to go to this bond to create the double bond.”*

Appendix 10: All responses containing the same illogical EPF arrow (arrow 208) for question 2.

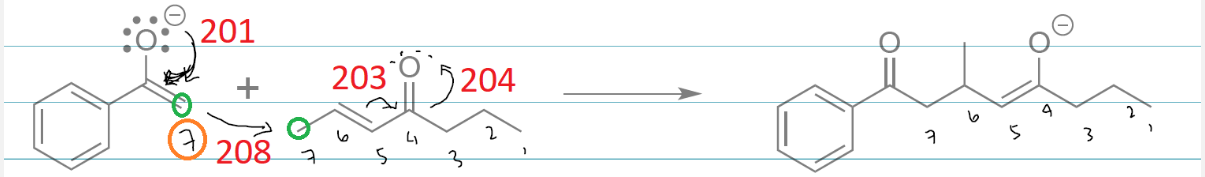
Question 2	
	
Int:	*"Is there anything about that one arrow that is going to link those two that um any um. What word am I thinking of . um. Um do you have any reason to believe I guess that is the arrow, or is really just a guess? […] I guess the question I have is are you more unsure about where the arrow, where it links to than like where it starts?"*
#02	*"I'm more confident about where it links to, that's because I think I have the like a habit of always moving the arrows from like this one to the other left side to the right side […] or I don't know, maybe it's just cause, like that's just how you read it. But I'm not sure."*
	
Int:	*"Um what information would tell you um that bond is going to form, or if electrons are going to move."*
#03:	*"Well um, if it had a charge, I would be able to move it. Like you know if it's pushing or pulling electrons. I don't remember exactly how it was attached, like how to attach the carbon here and the carbon here. *inaudible* oh actually. I'm just going to draw this again. That there, that would. Make this carbon lone pair. It doesn't want that lone pair. So it's going to give the lone pair to that *inaudible* and that would form a bond. And that would be a bond between the. And here they're attached."*
	
Int:	*"This arrow [arrow 208] is it point--pointing at that carbon there at the end or"*
#07:	*"yeah, yeah"*
Int:	*"thanks, um, tell me um, how did you identify uh, how to draw those arrows?"*
#07:	*"I just, I looked at the product--product side […] to see what changed from the two original reactants and then processed going backwards, is how I think"*



Int:	*“So what tells you, when you’re--you’re looking at something like this, what tells you that, um a bond is being formed or a bond is being broken.”*
#08:	*“Well, cause there's no bond there and then like a bond there […] like, what tells me that a bond has switched or like moved or like broken somewhere and formed somewhere else.”*
#08:	*“Well it’s just like comparing these I guess […] I just like, like for this, I kinda made a whole mess of this but like, this single bond, something had to have made a double bond here […] so I know there's another bond that wasn’t there before, so like I know a bond’s formed I just need to figure out where or how […] what’s formed that bond, does that kinda answer the question.”*



Int:	*“When you're trying to decide where to draw the arrows, what are- what's um what helps you decide what to do?”*
#09:	*“Um I like to look at the, the double bonds first […] Um, well I know that a double bond has the capacity to become a bond somewhere else or a pair of electrons, […] Versus like this little carbon, or yeah, I can't really, I guess I could move that but we don't usually move single bonds, they stay where they are, um and then again another indicator would be the negative charge.”*



205 206 207

Int:	*“What does the labeling tell you?”*
#11:	*“Oh the carbons? […] Um, the position of the car…, into each individual carbon”*
Int:	*“What did you label that one right there?”*
#11:	*“Oh seven ‘cause that’s kind of where it connects right now.”*
Int:	***“What about the other seven you have**? [circled in orange]”*
#11:	***“That’s just saying this is where it connects.”***
Int:	*“Would that help you being able to draw the arrow?”*
#11:	*“Well at this point I would just say this [Arrow 215].”*

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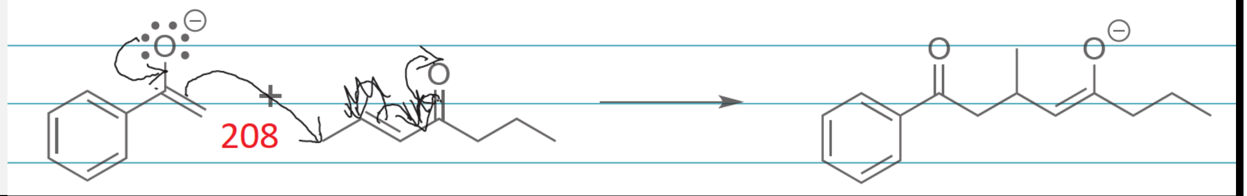
<tr><td colspan="2"> </td></tr>
<tr><td>**Int:**</td><td>*“So talk to me about how you decided to draw your arrows.”*</td></tr>
<tr><td>**#13:**</td><td>*“Um, I just, well first this one made sense to me because there was a charge and, like here it ends with a charge but I can see here that this one doesn't, so and there's a double bond so it looks kind of clear that these electrons needed to go somewhere […] So it would make most sense for them to go right there, onto and make another bond. Um and then I saw that there was no double bond between this carbon and the carbon that it was gonna be beside […] So I threw, so I threw those electrons onto here to help form the bond.”*</td></tr>
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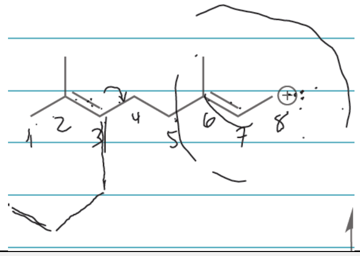
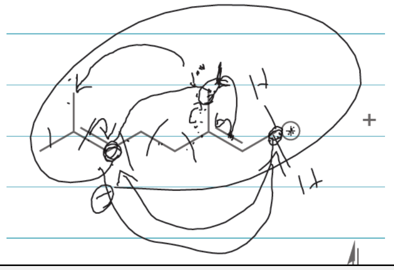
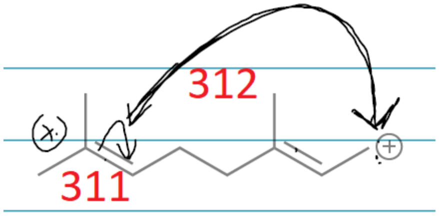
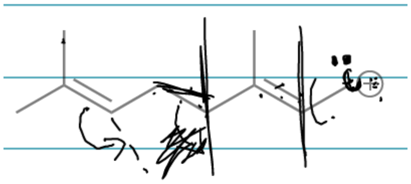
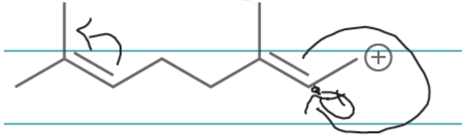
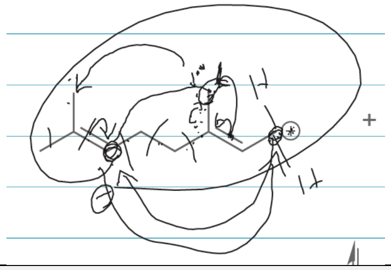
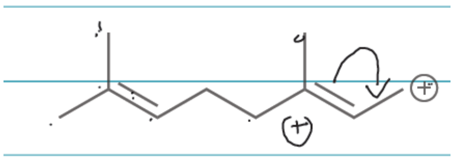
Appendix 11: All responses containing EPF arrows starting from the correct alkene question 3 step 2 of 3

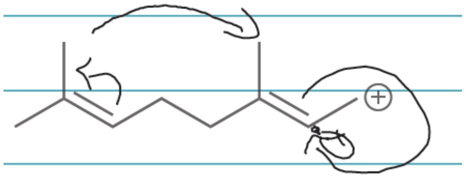
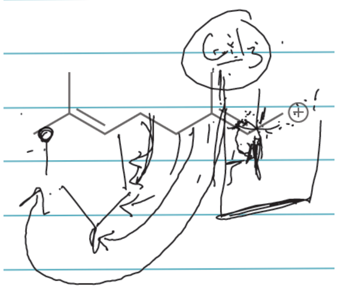
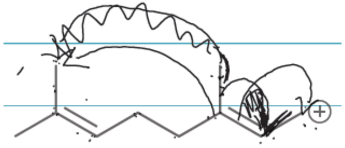
Participant #	Question 3 step 2 of 3 - proposed EPF arrows for ring formation
	
#01:	*“So, so far, um the ring is easy to make because the double. Can I show you? Or do I have to explain them right? “*
Int:	*“Sure yeah, sure. How do you want to show me?”*
#01:	*“Um,* ***because I numbered it here one, two, three, four, so that means that it is basically. So the ring Is easy to make. So four is going to stick out here. Five is going to stick out like that. Six is going to go like that. And a problem is there is a double bond here*** *[…] because* ***I have to figure out how that bond breaks and where the electron pairs move. And where to put the arrows****.* ***One two three four. Five. This is the part that really stumps me*** *[…]*
Int:	***“Are you counting the carbons to make sure there’s the same number****?”*
#01:	***“Mhmm that I’m not just going to make a random carbon****.”*
Int:	*“Would you like to move onto the next step? We can come back to it?”*
#01:	*“Sure, that’s what I should be doing maybe looking at the. Because I’ve been doing that earlier just looking at the products to see how it will end up. But. No I don’t think we need to go back actually.”*
	
#03	*“I see a ring. So that has to be formed. could I use the molecular model kit. […] that’s this. That’s this guy up here. So now I can do. Why are they not coming together? Now I can do that. And I’m getting more of what I’m looking for. Where I have this here. With that up here. And this here. So. That double bond is going to. I’m going to say. It’s going to go to that carbon then those two electrons are going to go to this double bond. There’s a few steps that have to happen but basically that double bond is going to put a lone pair of electrons on that carbon. And that’s going to give it a positive charge. So it’s going to want to pull. […] this carbon, or. It would have a negative charge, because it has a lone pair of electrons. Of three bonds. So then it’s going to want to give away it’s electrons. Because it will have a lone pair from moving them up this ladder. And then this lone pair is going to donate to that carbon. And uh. Basically attach them right. Here. So it would form a bond, so this bond right here. Would be formed. […] so. This. Oh. A double bond goes to*

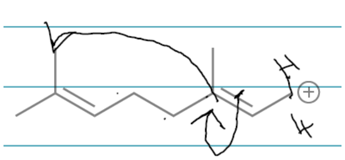
<table>
<tr><td></td><td>an atom, it forms a bond inbetween. Like as ingle bond between them right? So that would make an extra line in this, and that is not what we have.”</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>#04:</td><td>“okay um oh 'cause I th- it created- it created the cyclohexane, like the molec- this molecule itself created uh this cyclohexene, no cyclohexene […] Um so it must've, the positive end is over here so, this double bond must've, because there's only one double bond left and this one, so one of the double bonds must've broken in order to create the actual bond […] Because it's probably because of this formal charge that that cyclo- cyclohexane would uh, cyclohexene was probably created […] And I'm going to uh because uh there's a pi bond here, it created like an electron cloud so it would probably attract that formal charge, so this bond would probably be broken, yeah okay so I think this bond is broken, so this carbon uh […] This carbon would receive both electrons and this formal charge would, which way would it go, it would go this way to create like a bond with the, oh I wrote- I drew it the wrong way, whoops. Okay, this way so, that way […] Because, because this is a positive charge, it doesn't have the electrons […] Which created this cyclohexane ring, and then this one is left with a positive formal charge because it lost that bond, or the, the electrons from it”</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>#05:</td><td>“Mmm, okay so I think, so are the- okay so it's saying this carbon is positive [...] So, I don't think it's going to be the same carbon […] I don't think it's going to be the same one because like I still don't think, like I know I did it on the last page or whatever like 'cause- […] Or no, I guess not but like, I don't think- 'cause in order for this one to be um, the same one, you'd have to move some other carbons, like it just wouldn't make sense […] And here it's, there, it's got like two other carbons attached to it so I don't think it's the same one at all.”</td></tr>
<tr><td>Int:</td><td>“Okay, so how are you gonna connect it?”</td></tr>
<tr><td>#05:</td><td>“Okay so I can take this double bond and make it like this so it would be like this I guess […] So that gets rid of it, the double bond as well which is kinda what I needed, okay so yeah I think I got to what they wanted […] so I would take um, I know it's like really weird, but I take one of the double bonds and move it, okay so this one would become more like, I don't know how to show the arrow, but I'm not really moving it but like I'm just kinda straightening it out, kinda thing, I don't know, something s- […] Or this way, uh yeah, so I have like this part, like we'll just pretend that's the double bond there and then so, and then I have this part which is fine for like this part of the cyclohexane, then I want this part and this technically like straight and this isn't straight so I want</td></tr>
</table>

	it- I'm just trying to like straighten it up to conform to like the shape of like the cyclohexane?"
	
#07:	*"See if this double bon- which you connect this to close it off, this the double bond, is it at the same place as the bottom product. […] But it isn't so you have to move it over one, yeah you have to move it over so it fits. And then...double bond […] And then. That double bond splits all the way around, creating some of the most essential atom here and then the plus charge goes here. […] The double bond breaks up off that I guess not really break the pi bond just chan- changes conformation and just moves all the way around to I guess to creat- to create like a as you can say a [inaudible]. […] Um, I saw this double bond here, I saw the products, I saw that there is only one double bond in the pro- this new prod- this third step here so and there is an extra si-side chain to the compound and so there is a double bond so somehow that double bond changes and moves around to form a product."*

Appendix 12: All responses containing EPF arrows starting from the incorrect alkene question 3 step 2 of 3

Question 3 step 2 of 3	
	
#03	*“I see a ring. So that has to be formed. could I use the molecular model kit. […] that’s this. That’s this guy up here. So now I can do. Why are they not coming together? Now I can do that. And I’m getting more of what I’m looking for. Where I have this here. With that up here. And this here. So. That double bond is going to. I’m going to say. It’s going to go to that carbon then those two electrons are going to go to this double bond. There’s a few steps that have to happen but basically that double bond is going to put a lone pair of electrons on that carbon. And that’s going to give it a positive charge. So it’s going to want to pull. […] this carbon, or. It would have a negative charge, because it has a lone pair of electrons. Of three bonds. So then it’s going to want to give away it’s electrons. Because it will have a lone pair from moving them up this ladder. And then this lone pair is going to donate to that carbon. And uh. Basically attach them right. Here. So it would form a bond, so this bond right here. Would be formed. […] so. This. Oh. A double bond goes to an atom, it forms a bond inbetween. Like as ingle bond between them right? So that would make an extra line in this, and that is not what we have.”*
	
#06:	*“So well what I'm seeing here is this, there's a double bond inside the um, inside the, the, the ring so I'm going to assume that that means one of these, either this or this […] Um, might not get touched [...] So right now I'm trying to look for how, just how the ring forms really […] um again it's just um kind of going over it in circles, I I'm trying to find where they cyclohexane ring comes from […] Just because it has those one, two, three, four, the same as this, one, two, three, four. Plus it has the double bond here, so um and the double bond is here as well […] Also, this methyl group coming off of it, it's, just seems very convenient to have it that way […] Well this has- this is sp3, it has all its hydrogens, it doesn't have any lone pairs coming off of it, um there's nothing, there's no real movement. It wants to do, it wants to just kinda stay […] Stay as it is 'cause it's happy as is. So, also if it were to bond here then I would have a group coming out here, here and here which just doesn't coincide with how it is down here […] So I think I'm stuck, I'm not sure”*

	
#07:	*“See if this double bon- which you connect this to close it off, this the double bond, is it at the same place as the bottom product. […] But it isn’t so you have to move it over one, yeah you have to move it over so it fits. And then...double bond […] And then. That double bond splits all the way around, creating some of the most essential atom here and then the plus charge goes here. […] The double bond breaks up off that I guess not really break the pi bond just chan-changes conformation and just moves all the way around to I guess to creat-to create like a as you can say a [inaudible]. […] Um, I saw this double bond here, I saw the products, I saw that there is only one double bond in the pro- this new prod- this third step here so and there is an extra si-side chain to the compound and so there is a double bond so somehow that double bond changes and moves around to form a product.”*
	
#08:	*“this one has to be apart of this like, this little group here. Heart that just doesn’t belong in the cyclic part which becomes this part. So that’s where we get 3 carbons, 1 2 3. And this bond sort of just moves up and forms a iso-propyl group […] it doesn’t really like matter where it goes, it kind of just makes a. I think it’s an iso-propyl kind of thing. Cause we have our propyl groups, and it kind of just makes a line, so we have our one two three and they kind of bind together like that and they just bind off the middle onto here. So I’m. uh. Yeah, so if we take one of these. If we show you. If the double bond […] we take one, and sort of move it down, then we get our proply thing here. As well as we can have a bond here. I’m just saying to move the electrons. And that’s how we bond onto the bottom, using the electrons from this double bond and that becomes this bond.”*
	
#12:	*“Um okay so you have to form a cyclohexane. Um, s- and with that you have um, so that's isopropyl, um and you have um a methyl group. So um I’m g - like because of this structure, I'm going to assume that this part is this […] Um so I'm going to leave this as a methyl group and just, and since this bond is like that one I'm just going to um, kind of close […] Um the cyclohexane. So um (...) you have to like, (laughs) I don't know how to explain that um, so I guess the, so this carbon, (drawing) so I go here, um and then (...drawing) um well if those two connect then everything should*

<table>
<tr><td></td><td>match up because one, two three, four, five, six. […] so what you would do is you'd have to like break this double bond […] Um but you have to keep, you still have to keep one of them charged um and so (...) um (...drawing) you would I guess like break this.”</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>#13</td><td>”But because I see an extra double bond here that I don't see in- […] Another, so that wouldn't really make, but there's one double bond and that's beside the thing that's sticking up, so it makes sense that this would turn into the th- methyl group up here and this would form a bond with something […] So I'm gonna, what if I do one, two, three, four, five, six, I think that if these el- this, the electrons from this double bond I think if this bond breaks and the electrons go to this carbon, then this carbon can form a bond over here […] And we'll have one, two, three, four, five, six, so it would make a ring and then um (...) and then yeah we'd have three carbons here and one of them is positive, see I think that makes sense.”</td></tr>
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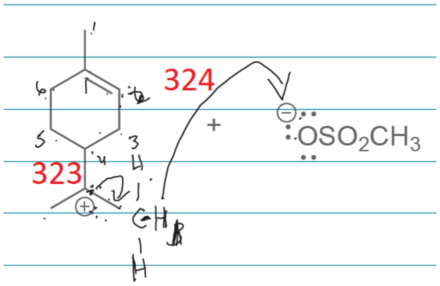
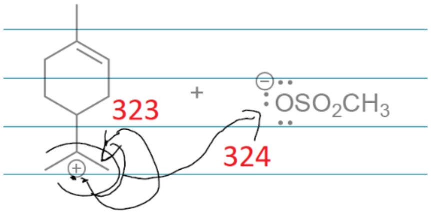
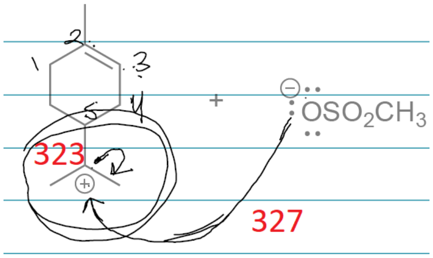
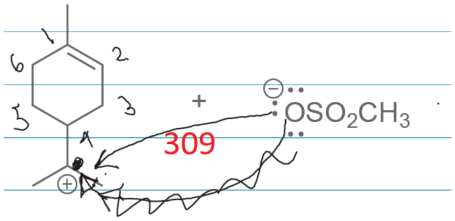
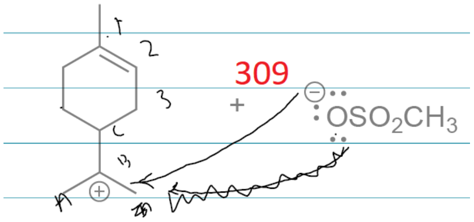
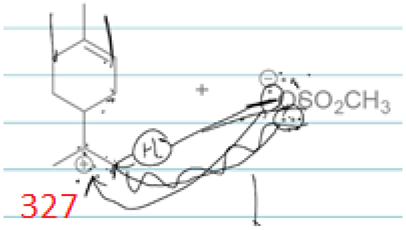
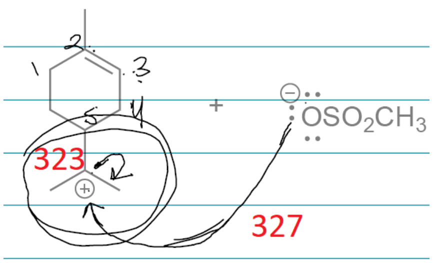
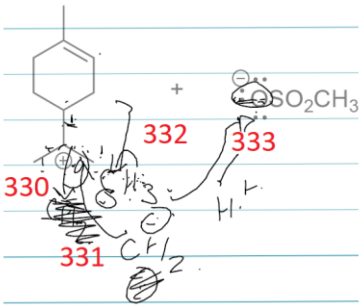
Appendix 13: All responses containing reversed EPF arrows for question 3 Step 3 of 3

Participant #	Question 3 Step 3 of 3
	
#01:	*"I'm wondering where this hydrogen came from. […] and there's a double bond to make the. And there's no formal charges so that means that the charge probably made a. lets see how many electrons would this one have? Because there's a positive charge. It only has six […] I'm trying to figure out how there's a double bond here […] oh okay, because it's connected to CH3 over here. I was wondering where the hydrogen came from. So now because it's a double bond, it's going to become a CH2. Um so then the electron is . this positive charge I guess that is the electron. Um. Carbon bond.. […] I would draw carbon. Like that. And then I would draw this one here and this is specifically to the hydrogen. […] just one, so it would be. Three there for example. H H H and like that. And this hydrogen goes to this charge over here. And that's why there's no charge on that side caus e then you'd have that and you'd have to share these electrons."*
	
#07:	*"Um, this third step here it had to, um, there were no charges anywhere, the charge was indicating that something wasn't full, it's octet wasn't full. And then the final step it showed that- you need- the double bond was I guess formed and then you needed to chan-, there was no more charges anywhere so it indicated that the charges somehow had to move somewhere and then fill up an octet or change into like a bond of some sort and then just disappear. Or change into a double bond and then it has to react with something. And then yeah […] I just know the positive charge has to move somewhere, cause they weren't apparent in the final product. […] Yes, 'cause you had- they also indicate that bonds are broken and then things change so you have to move stuff around as well."*

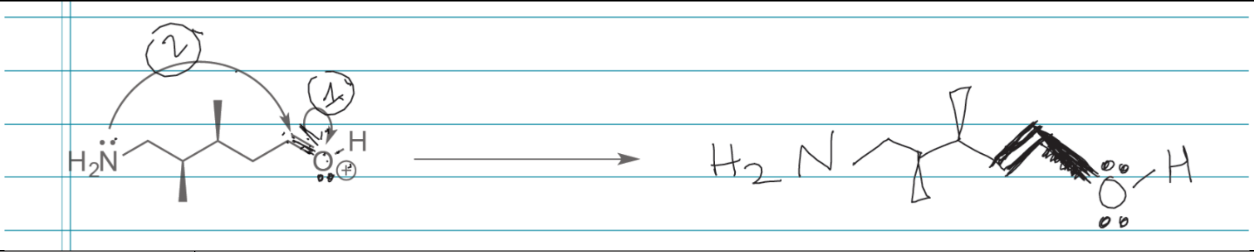
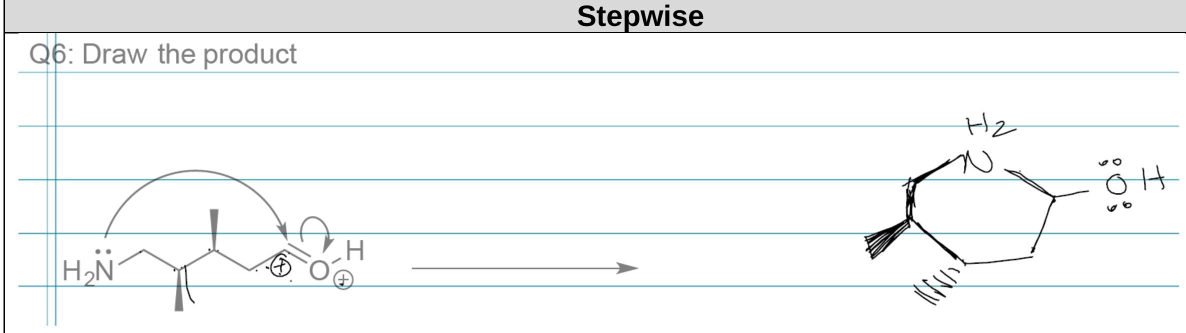
	
#09: **(arrow 323)**	*“um yeah this somehow, this all becomes this and then there's an extra hydrogen left over […]For that but I'm not sure […]So that first part of the molecule's good, it's this that that changes […]That' I'm not sure about, like how it changes […]and then I'm pretty confident about this whole double bond […] negative positive thing, but then there's somehow that extra hydrogen that I'm not sure about and I think that comes from that […]But I, I don't know how to explain that.”*

Appendix 14: All responses illogical EPF arrows for question 3 Step 3 of 3

EPF arrow from the electrons on oxygen to carbon-carbon bond	
	
Int:	*"So can we go through it one more time, so the electrons from the oxygen."*
#02:	*"Move to bond [arrow 309] between the two carbons over here. And that created the double bond, and then when that happened, the hydrogen. I don't know how, the hydrogen here. I guess moved as well. And it responded to this molecule which makes that."*
	
#11	*"Um, the cyclo [whisper], cyclohexane formed a double bond near the bottom [inaudible] the positive. […] And then the oxygen sulfur thing got an extra oxygen. […] Excess electrons I guess. […] At the oxygen part but. I don't really know where it would go. […] I have an idea but it's like 99 percent wrong […]It doesn't even look legit in my head. […] I just moved that negative over. […] I kind of want to say that one electrons moves over, so it forms the double and then since it has the extra electron on the oxygen, oxygen comes in but I don't-I don't really think that's how chemistry works."*
Int:	*"Um would you want to draw what you have in your head even if you are not sure?"*
#11	*"Um, yeah it looks like that. [arrow 309]."*
Direct EPF arrow from negative to positive charges	
	
#05 (arrow 327)	*"Okay so it has like no charge here (...) oh okay yeah so I gue- kay so like one I guess pair here to get rid of the charge difference, right so […] And then, I want to say like something happened with this electron as well to make like the double bond that happens here […]'Cause, I guess there was, kay so there was a hydrogen somewhere here, maybe it was like attached to this one, so this cabron*

	[…]So then, when, oh okay so then, so if it's like this then this hydrogen went over and took like the bind(bond?) with the- this oxygen here […] So now this carbon has like extra electrons that it's not binding with any hydrogen with […]So maybe it used it to make like a double bond.”
	
#09 (arrow 327)	*“Um yeah this somehow, this all becomes this and then there's an extra hydrogen left over […]For that but I'm not sure […]So that first part of the molecule's good, it's this that that changes […]That' I'm not sure about, like how it changes […]and then I'm pretty confident about this whole double bond […] negative positive thing, but then there's somehow that extra hydrogen that I'm not sure about and I think that comes from that […]But I, I don't know how to explain that.”*
Cluttered illogical EPF arrows	
	
#08	*“I’m thinking about taking the electrons off with this hydrogen. So that would just be an H, but it actually comes off as just the, proton. Like the electrons go into this guy, […] and so they make him negative, so it would actually become a CH2 with a negative charge, and this would become an H plus and so then that H plus would go over to here and just become an H, which is what we have here. And by like doing that, by forming the bond here instead of having the lone pair, we uum like. I don’t want to say get rid of, but we like sort of equal out, equalize, equal um neutralize maybe, I don’t know the proper term for it is, […] we get rid of the formal charge, by adding on this positive hydrogen, um and then to deal with this negative charge here because C carbon is not an electronegative atom. We make a double bond, we like take these electrons. Let me draw it here.”*

Appendix 15: Examples of a Concerted, Concerted and Stepwise, Stepwise, Unsure, and Undecided.

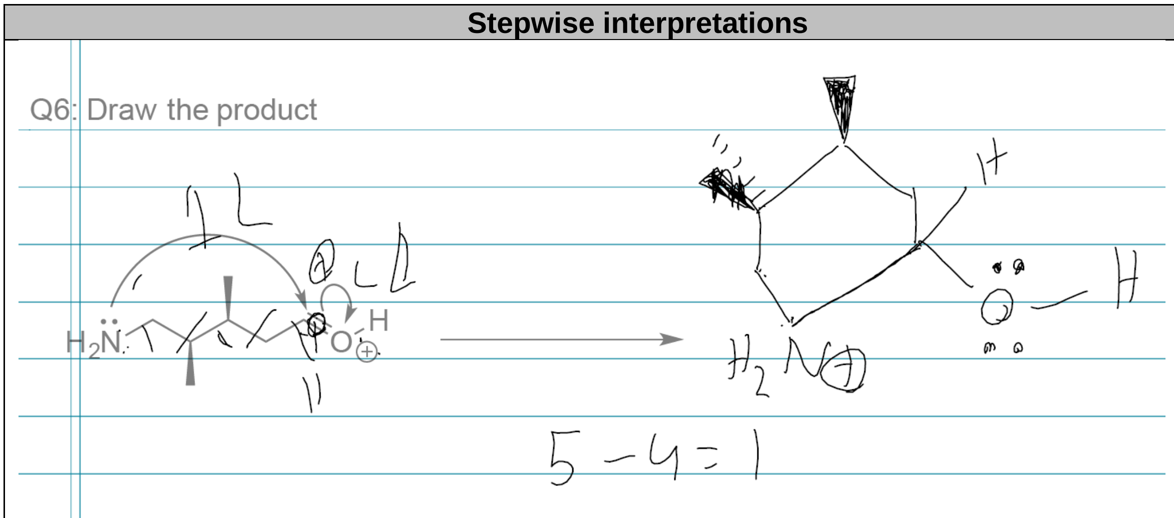
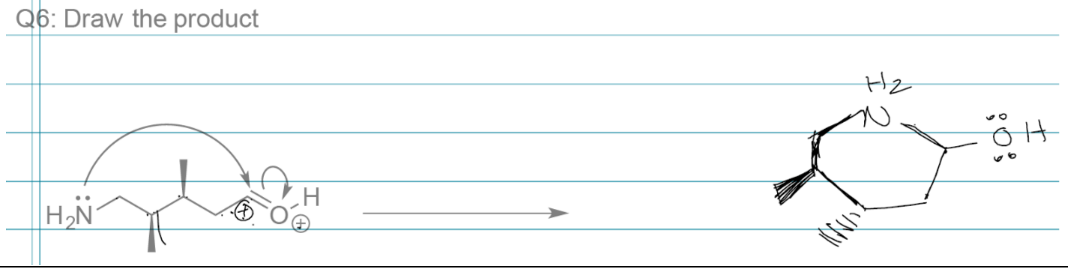
Examples	
Concerted	
Int:	“When you talk about that happening. When you picture it in your mind, do you picture it all at one time, one step after another? How do you picture that in your mind, just that one step?”
#02:	*“that one step? **I picture it happening simultaneously**.”*
Concerted to Stepwise Part 1 of 2	
	
Int:	“So each step here I guess has two curved arrows for each um step, do you think that those um, how do yo- how do those happen in your mind, um do they happen one after another or do they happen at the same time?”
#05:	*“Um, I think they kind of **happen at the same time** for me, to be honest… Yeah, so I feel like, **I feel like in order for like one to happen the other has to happen as well**.”*
Concerted to Stepwise Part 2 of 2	
Int:	*“Do you think there's an order to how this process happens, so if you had this one step here with these two arrows, um do you think they happen at the same time or do you think one happens before the other?”*
#05:	*“I **think this one is like number one, and this is number two, so I think this one has to happen before this one does** because again I don't think that oxygen can have like um an extended octet and like at the same time this already has that, oh well I guess you could have a triple bond, but like, I actually didn't even think about that, so if you did the triple bond here… Like switch it up but it doesn't make sense because, again you'd have like, you'd still have to move this arrow here no matter what and it just, it would be more than eight bonds so it wouldn't make sense, so yeah I think this one has to be like step number one.”*
Stepwise	
 Q6: Draw the product	
Int:	*“Okay, yeah um, did you think about the, and I, I think you probably just talked a little bit about this, so I was going to ask about the order of the arrows this time, if one happens before the other one or if they happen at the same time.”*

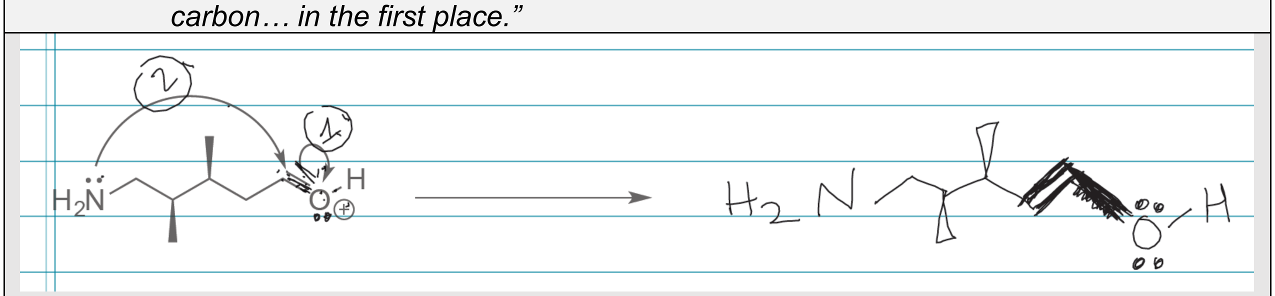
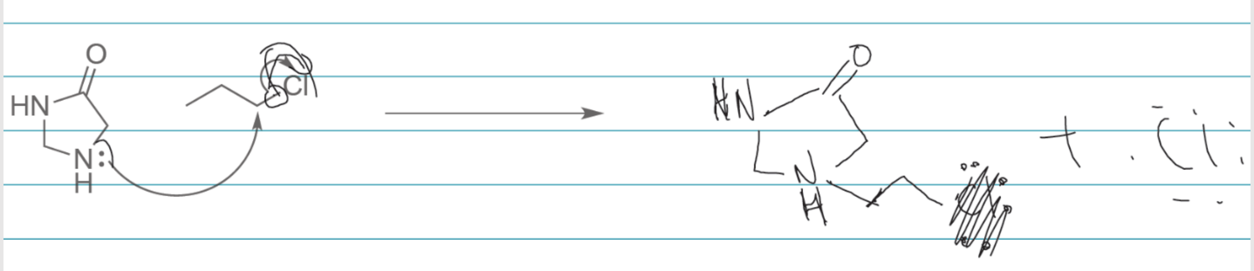
#04:	*“I think, yeah I think 'cause I saw that positive charge first I kind of figured, the elec- those- the* ***electrons would move there first and then the second positive charge is made, and then that would- the electrons would move****. Or else like the electron kind of doesn't really have a reason to move, there's no positive charge on the carbon… in the first place.”*
Unsure	
Int:	*“So do you think um that the curved arrows um happen at the same time, do you think that there's an order to them, so if you're thinking about how it happens in your mind, um how do you think about that?”*
#09:	*“Yeah, there's there should generally be two,* ***I think if not always there's going to be the first curved arrow and then the second so um the first one****, especially if I'm looking at this, comes right from a pair of electrons… And then it goes to either a bond or molecule itself, and then, and then this is not scientific but from there there's gonna be a second arrow that doesn't r- it's always shorter, you see.”*
Unsure	
Int:	*“And do you think that it happens in that order in your mind, or is it, let me just pick the one to start with first?”*
#09:	*“Well um, I know that that is, remember when we talked about,* ***there were like first and second arrows****?..* ***I'm pretty sure that that's the second arrow****… Um and I don't think* ***I should start with that one, because we always start with the first one, but I don't know it's just easier for me to see because there were electrons right there****.”*
Undecided	
Int:	*“So if you're picturing this happening in your mind um do you think that what's going on in each step is happening simultaneously or do you picture it kinda happening sequentially, one after the other?”*
#13:	*“Um, hm uh no I don't,* ***I think, in my head to make the problem easier I picture it happening one at a time****, like I picture if... Oh well if these electrons move here then we have to flow these here…* ***But I don't know whether it, like in real time if it would happen all at the same time or not*** *(laughs).”*

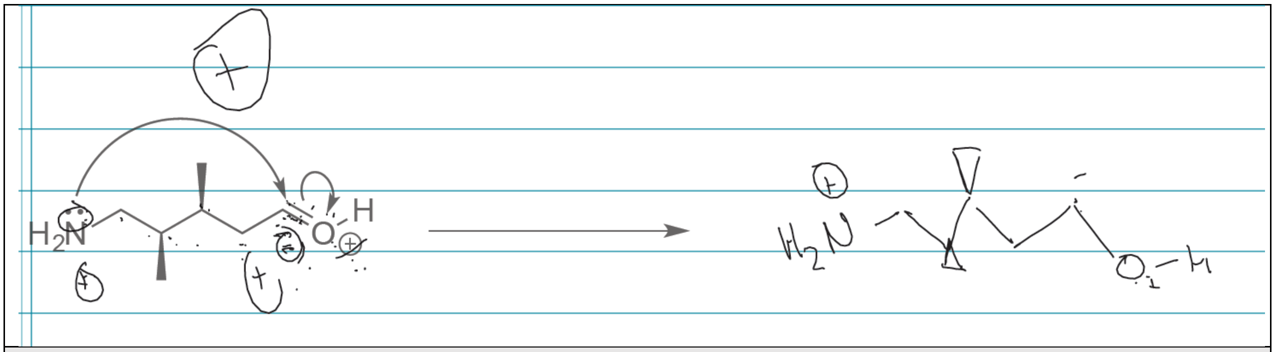
Appendix 16: All responses that indicated approaching the EPF arrows stepwise is easier

Participant #	Interpreting singularly is easier than concertedly
#01:	*“**I think it happens all at once, but to make it easier, it would be easier to do it step by step.**”*
#06:	*“**I kinda do it step by step with multiple arrows**… **Just to help myself understand it**, but it's not uh again we haven't done reaction mechanisms yet in class so I'm, **I'm pretty sure they're supposed to happen almost simultaneously if it's shown in the same step**… But usually the way it happens is I, **the first arrow that I decipher**… How it works, **I just think oh okay that that that's number one, that happened first, and then the next arrow I look at number two, why is it happening and what is happening**... But the- it could be either or, like um **for instance in this case if I look at this arrow** (arrow 2) **… As number one, I'd just see okay so it bonds here, the carbon is electronegative, it doesn't like being electronegative so it, this bond here breaks** (arrow 1) **and then the valence pair goes to the electropositive oxygen**, uh it, **it works either way, it's just again whichever one I happen to decipher first** … **Usually it's the easier arrow, or like the shorter arrow in this case**… So it, in my mind I, **I see it in my mind when deciphering it as it being first step, second step, for two arrows are first step second step, third step for three arrows**, … **But that's that's just a tool I use I guess** ... **To figure it out**.”*
#07:	*“yes, I think not all four steps happen at the same time It’s just this is like a simplified--it’s the easiest way to show the reaction but there are many--there’s four, there’s clearly four steps that happen to it there’s the simplest [inaudible]cleanest, I guess way to show it compared to like the other one on the other side I believe so, It’s left to right cause it’s logically more--you could go the other way I think too, but yeah I guess it has to go a certain direction for it to actually work or else you can’t just,ah change this--change random bonds everywhere […] the four is just a way to process the way I think, it makes it much more, I guess, organized and **easier to think of but it my head it probably, it just happens spontaneously at the same time”***
#12:	*“I just picture them going so from what you have first, so generally like on the left side going to the right side and then coming backwards. **But I do know that they're technically supposed to be happening simultaneously**, but like **in my head I just always pictured going from one to the other and then back** … Uh, **because it helps, I guess, um me to better visualize, like what is happening**…. Um because **if I picture them at the same time then I get them all mixed up with the electrons, like where they go** and- … uh umm I find, yeah it helps um to think of it that way. **Whereas, at the same time it's just too much at the- like at once**.”*
#13:	*“**I think, in my head to make the problem easier I picture it happening one at a time**, like I picture if… Oh well if these electrons move here then we have to flow these here. But I don't know whether it, **like in real time if it would happen all at the same time or not.**”*

Appendix 17: All responses containing cause-and-effect problem-solving discussion of EPF arrows

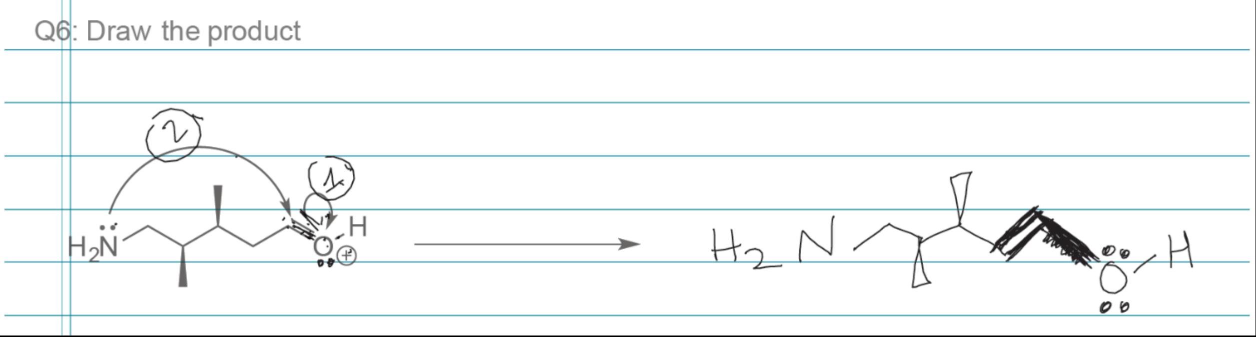
Stepwise interpretations	
	
Int:	*"I know in some of the previous questions I've asked you about. Do the arrows happen sequentially or at the same time? Is there an order to the electron movement here?"*
#03	*"**I guess for one thing to happen, one thing has to happen first**. So like for this, the double bond here to break and give oxygen two electrons or a lone pair of electrons, it won't do that without having a reason, it would rather stay neutral… this carbon over here. Rather stay neutral. Instead of becoming. Become positive. Yeah it would become positive. **That would happen without this bond attaching. So I'm saying I guess this would have to happen first. I don't know. I guess that could happen and then this could happen. Or they could happen at the same time. I don't know**. I'm trying to think of why but I'm not sure of the theory behind it… yeah, because if this happens and this double bond breaks. The carbon then wants to become neutral. And I would assume it would pull the nitrogen. Because it has a positive charge, so it's going to want to pull. But if this happens first, and it puts five bonds on the oxygen, the carbon, **because that should never happen because it would break its octet rule and it would give it a formal charge of negative one**. So that is going to push away electrons**. So then that would make this happen. So then either way it could happen in either order. like it could be the first step then this, or this be the first step then this… yeah**. **Because I don't think it can happen at the same time**?... because **I think that it should be one happens and then it must happen**. **More of a chain reaction** rather than boom. And it's all done… I feel like this causes that, or this causes that. I don't know which one."*
	

Int:	*“Okay, yeah um, did you think about the, and I, I think you probably just talked a little bit about this, so I was going to ask about the order of the arrows this time, if one happens before the other one or if they happen at the same time.”*
#04:	*“I think, yeah I think 'cause I saw that positive charge first I kind of figured, the elec- those- the* ***electrons would move there first and then the second positive charge is made, and then that would- the electrons would move****. Or else like the electron kind of doesn't really have a reason to move, there's no positive charge on the carbon… in the first place.”*
	
Int:	*“Do you think there's an order to how this process happens, so if you had this one step here with these two arrows, um do you think they happen at the same time or do you think one happens before the other?”*
#05:	*“I* ***think this one is like number one, and this is number two, so I think this one has to happen before this one does*** *because again I don't think that oxygen can have like um an extended octet and like at the same time this already has that, oh well I guess you could have a triple bond, but like, I actually didn't even think about that, so if you did the triple bond here… Like switch it up but it doesn't make sense because, again you'd have like, you'd still have to move this arrow here no matter what and it just, it would be more than eight bonds so it wouldn't make sense, so yeah I think this one has to be like step number one.”*
	
Int:	:Okay. thank you. Um so um you have two arrows drawn here so um tell me if you picture this reaction happening in your head do the arrows happen one after the other, do they happen at the same time? What do you picture in your mind?”
#07:	“They have to happen at the sa- Oh no. **The one that- the delocalization of electrons has to happen first because the carbon cannot exceed his oct**et. So that happens first and the- hmm. **No the chlorine has to delocali- to detach from that carbon ‘cause before the electrons can attach- make a new bond with the carbon- end carbon**, ‘cause the octet will be overflo- overfilled and you can’t have that with the carbon.”



Int:	“so here is the question I have for this one, so does one of these arrows happen before the other one? Or do they happen at the same time”
#08:	“**well this one has to occur beforehand because we can’t put another lone pair on there**. like this doesn’t have a charge so I’m assuming this has a hydrogen bonded onto here m, so this of course has to happen first and I think this would like naturally just happen because of the. Bad charge here. When I say bad charge I mean not stable. Unstable charge. Um but I don’t know if this would naturally just occur. Like I guess it would, yeah it would have to, we cant just have a negative on this carbon by taking away like this bond and putting it on here. Um, nonono what am I saying. **We cant just have a positive on this carbon by taking away the bond, like this would make a positive charge by taking away the negative bond um, so we have to put this on here I guess. So this would happen afterwards but this is more of a reaction towards what is happening here**.”
Int:	*“Okay, okay. So um for this one there's like, four or five arrows going on, so do you think that these happen in a order, I mean they're all in one step here, but do you think that there's a secret to them, or that in reality they happen at once but we just draw them one at a time?”*
#12:	*“**Um, well like I think to a certain degree there has to be um, some steps because you can't have just everything going on at once**. Um but I think it like happens really really fast, so it seems simultaneous, um but something has to start the, the reaction because um, I don't think there's anyway from them to know, just like okay so all of us at once, like all the electrons are just going to move (interviewer laughs), um and it's going to work out. **So something has to start it, and then from there it's like a chain reaction of what happens.**”*
	Concerted interpretation
#06:	*“**I kinda do it step by step with multiple arrows**…**Just to help myself understand it**, but it's not uh again we haven't done reaction mechanisms yet in class so I'm, **I'm pretty sure they're supposed to happen almost simultaneously if it's shown in the same step**… But usually the way it happens is I, **the first arrow that I decipher**… How it works, **I just think oh okay that that that's number one, that happened first, and then the next arrow I look at number two, why is it happening and what is happening**... But the- it could be either or, like um **for instance in this case if I look at this arrow*** (arrow 2) ***… As number one, I'd just see okay so it bonds here, the carbon is electronegative, it doesn't like being electronegative so it, this bond here breaks*** (arrow 1) ***and then the valence pair goes to the electropositive oxygen**, uh it, **it works either way, it's just again whichever one I happen to decipher first** … **Usually it's the easier arrow, or like the shorter arrow in this case**… So it, in my mind I, **I see it in my mind when deciphering it as it being first step, second step, for two arrows are first step second step, third step for three arrows**, … **But that's that's just a tool I use I guess** ... **To figure it out**.”*

Appendix 18: All participants responses containing both a concerted and stepwise interpretations.

Concerted to Stepwise interpretations	
 Q6: Draw the product	
Int:	*“So each step here I guess has two curved arrows for each um step, do you think that those um, how do yo- how do those happen in your mind, um do they happen one after another or do they happen at the same time?”*
#05:	*“Um, I think they kind of **happen at the same time** for me, to be honest… Yeah, so I feel like, I feel like in order for like one to happen the other has to happen as well.”*
Int:	*“Do you think there's an order to how this process happens, so if you had this one step here with these two arrows, um do you think they happen at the same time or do you think one happens before the other?”*
#05:	*“I **think this one is like number one, and this is number two, so I think this one has to happen before this one does** because again I don't think that oxygen can have like um an extended octet and like at the same time this already has that, oh well I guess you could have a triple bond, but like, I actually didn't even think about that, so if you did the triple bond here… Like switch it up but it doesn't make sense because, again you'd have like, you'd still have to move this arrow here no matter what and it just, it would be more than eight bonds so it wouldn't make sense, so yeah I think this one has to be like step number one.”*
Concerted – Question 1	
Int:	*“So do you think that there’s an order to those four arrows that you drew.”*
#07:	*“The four is just a way to process the way I think, it makes it much more, I guess, organized and easier to think of but it my head it probably, it just happens spontaneously at the same time.”*
Stepwise - Question 5	
Int:	*“Okay. thank you. Um so um you have two arrows drawn here so um tell me if you picture this reaction happening in your head do the arrows happen one after the other, do they happen at the same time? What do you picture in your mind?”*
#07:	*“They have to happen at the sa- Oh no. The one that- the delocalization of electrons has to happen first because the carbon cannot exceed his octet. So that happens first and the- hmm. No the chlorine has to delocali- to detach from that carbon ‘cause before the electrons can attach- make a new bond with the carbon- end carbon, ‘cause the octet will be overflo- overfilled and you can’t have that with the carbon.”*
Concerted – Question 1	

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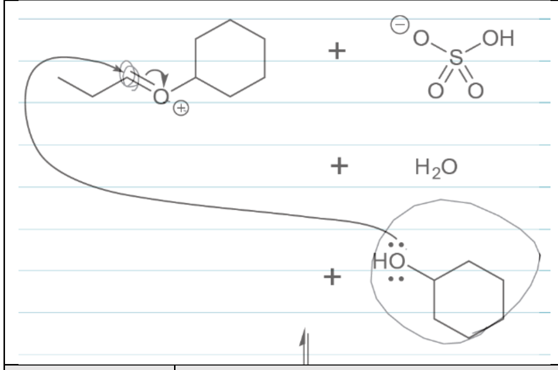
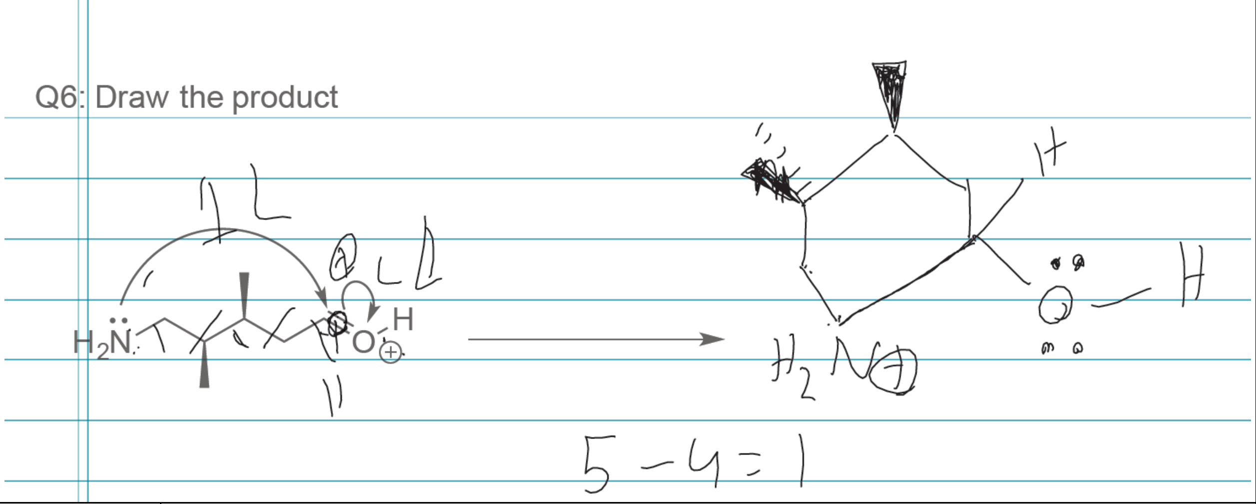
<tr><td colspan="2"> </td></tr>
<tr><td>Int:</td><td><i>“So when you said that this oxygen comes in and then this bond has to move. Do you picture that in your head happening one after another?”</i></td></tr>
<tr><td>#03:</td><td><i>“I guess it would have to happen at the same time I guess, because like simultaneously I guess the double bond. The carbon can’t have more in its octet. So as it is happening, that has to happen simultaneously. I would think. So it doesn’t screw up with the octet rule. And now that becomes part of this over here.”</i></td></tr>
<tr><td colspan="2">Stepwise – Question 6</td></tr>
<tr><td colspan="2"> </td></tr>
<tr><td>Int:</td><td><i>“I know in some of the previous questions I’ve asked you about. Do the arrows happen sequentially or at the same time? Is there an order to the electron movement here?”</i></td></tr>
<tr><td>#03</td><td><i>“I guess for one thing to happen, one thing has to happen first. So like for this, the double bond here to break and give oxygen two electrons or a lone pair of electrons, it won’t do that without having a reason, it would rather stay neutral… this carbon over here. Rather stay neutral. Instead of becoming. Become positive. Yeah it would become positive. That would happen without this bond attaching. So I’m saying I guess this would have to happen first. I don’t know. I guess that could happen and then this could happen. Or they could happen at the same time. I don’t know. I’m trying to think of why but I’m not sure of the theory behind it… yeah, because if this happens and this double bond breaks. The carbon then wants to become neutral. And I would assume it would pull the nitrogen. Because it has a positive charge, so it’s going to want to pull. But if this happens first, and it puts five bonds on the oxygen, the carbon, because that should never happen because it would break its octet rule and it would give it a formal charge of negative one. So that is going to push away electrons. So then that would make this</i></td></tr>
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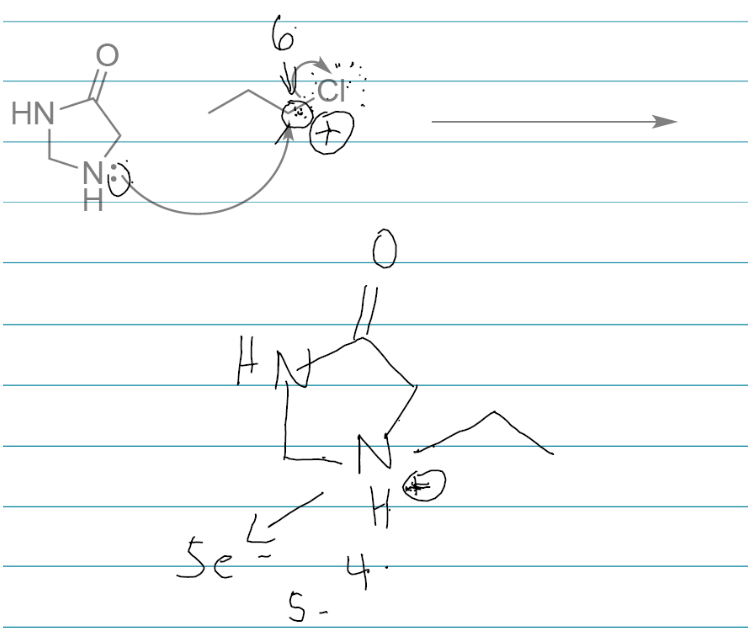
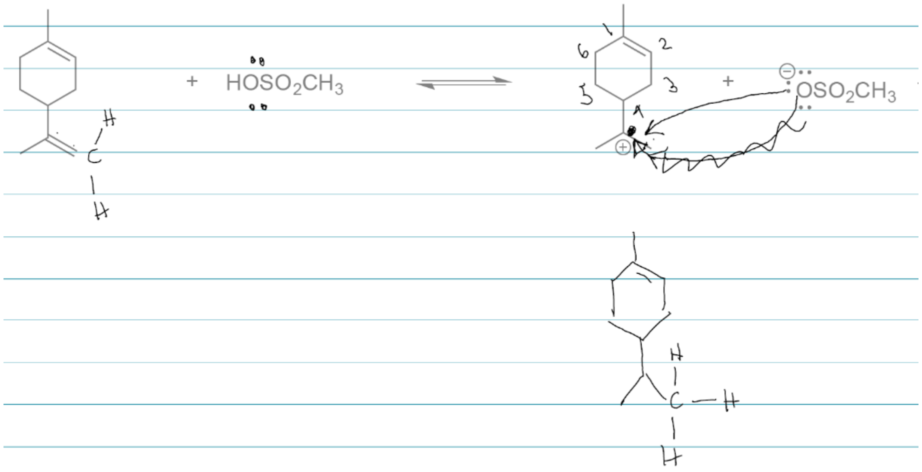
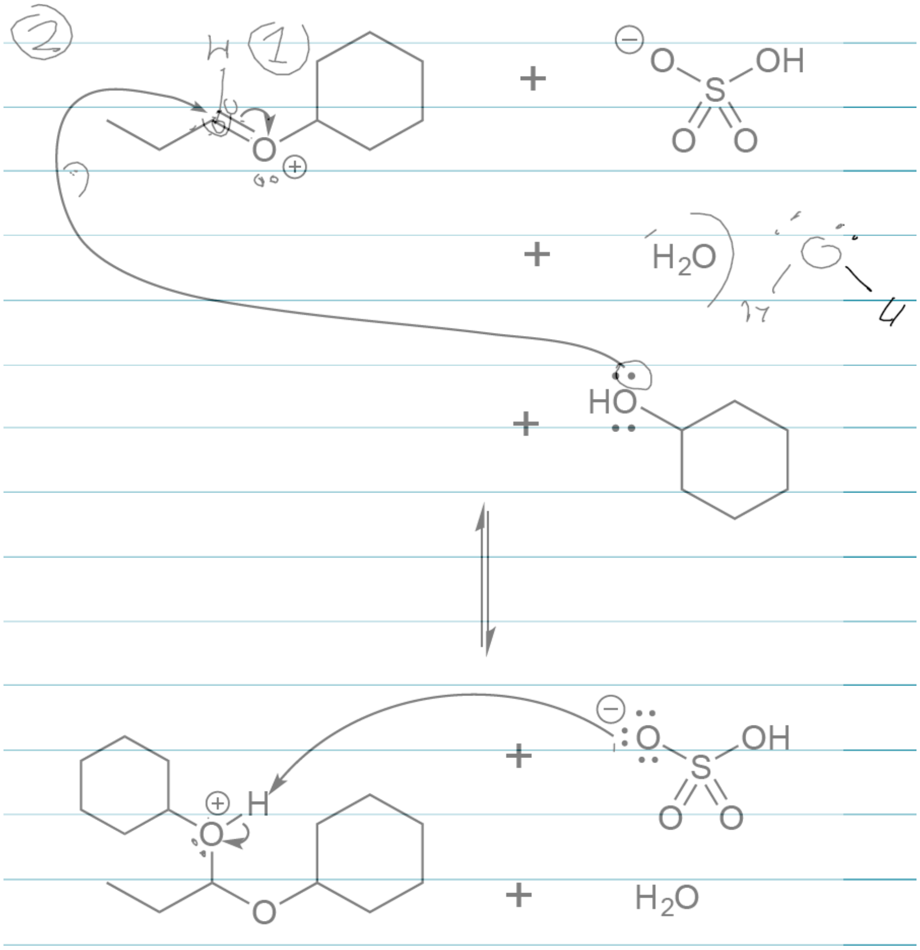
	happen. So then either way it could happen in either order. like it could be the first step then this, or this be the first step then this… yeah. ***Because I don't think it can happen at the same time****?... because* ***I think that it should be one happens and then it must happen***. ***More of a chain reaction*** *rather than boom. And it's all done… I feel like this causes that, or this causes that. I don't know which one.”*
Concerted - Question 1	
Int:	“Okay, okay. Thank you. Um so each step here um I think has two arrows, I think, yeah so um when a reaction step has two electron pushing arrows um, if you're going to picture that happening in your mind, um, do you picture that those happen, I guess, simultaneously, or do you picture them one after the other, and if so kind of how do you decide?.”
#12:	*“I just picture them going so from what you have first, so generally like on the left side going to the right side and then coming backwards. But I do know that they're technically supposed to be happening simultaneously, but like* ***in my head I just always pictured going from one to the other and then back*** *… Uh,* ***because it helps, I guess, um me to better visualize, like what is happening****…. Um because* ***if I picture them at the same time then I get them all mixed up with the electrons, like where they go*** *and- … uh umm I find, yeah it helps um to think of it that way.* ***Whereas, at the same time it's just too much at the- like at once****.”*
Stepwise – Question 2	
Int:	*“Okay, okay. So um for this one there's like, four or five arrows going on, so do you think that these happen in a order, I mean they're all in one step here, but do you think that there's a secret to them, or that in reality they happen at once but we just draw them one at a time?”*
#12:	*“Um, well like I think to a certain degree there has to be um, some steps because you can't have just everything going on at once. Um but I think it like happens really really fast, so it seems simultaneous, um but something has to start the, the reaction because um, I don't think there's anyway from them to know, just like okay so all of us at once, like all the electrons are just going to move (interviewer laughs), um and it's going to work out. So something has to start it, and then from there it's like a chain reaction of what happens”*

Appendix 19: All responses containing concerted interpretations.

Concerted interpretations	
	
Int:	"Okay to recap, does it happen at one time or all at once, or do you think one arrow happens and then the next."
#01	"*I think it happens all at once, but to make it easier, it would be easier to do it step by step.*"
	
Int:	"so can we go through it one more time, so the electrons from the oxygen"
#02:	"move to bond between the two carbons over here. And that created the double bond, and then when that happened, the hydrogen. I don't know how, the hydrogen here. I guess moved as well. And it responded to this molecule which makes that"
Int:	"When you talk about that happening. When you picture it in your mind, do you picture it all at one time, one step after another? How do you picture that in your mind, just that one step?"
#02:	*"That one step? **I picture it happening simultaneously**."*



#06:	“***I kinda do it step by step with multiple arrows***… ***Just to help myself understand it***, *but it's not uh again we haven't done reaction mechanisms yet in class so I'm,* ***I'm pretty sure they're supposed to happen almost simultaneously if it's shown in the same step***… *But usually the way it happens is I,* ***the first arrow that I decipher***… *How it works,* ***I just think oh okay that that that's number one, that happened first, and then the next arrow I look at number two, why is it happening and what is happening***... *But the- it could be either or, like um* ***for instance in this case if I look at this arrow*** *(arrow 2)* ***… As number one, I'd just see okay so it bonds here, the carbon is electronegative, it doesn't like being electronegative so it, this bond here breaks*** *(arrow 1)* ***and then the valence pair goes to the electropositive oxygen***, *uh it,* ***it works either way, it's just again whichever one I happen to decipher first*** … ***Usually it's the easier arrow, or like the shorter arrow in this case***… *So it, in my mind I,* ***I see it in my mind when deciphering it as it being first step, second step, for two arrows are first step second step, third step for three arrows***, … ***But that's that's just a tool I use I guess*** ... ***To figure it out***.”
Int:	*“Um, so um, many of these steps we have seen today have two curved arrows in each step. Do you think that they happen um, at the same time those curved arrows or do you think that there is an order to them.”*
#11:	“***If you move an electron over there you’re gonna have one extra and then that octet isn't really an octet anymore... So I feel like it kinda happens at the same***

	***time where it removes one of the electrons and then the other kinda just jumps in**… because **if it did have an order, that would mean like let's say this electron moves over here it would have an extra and that won't be stable for the carbon**. Um, so like- or similar to when it um removes the double bond that would cause it to be like not an octet."*

Appendix 20: All responses containing stepwise interpretations

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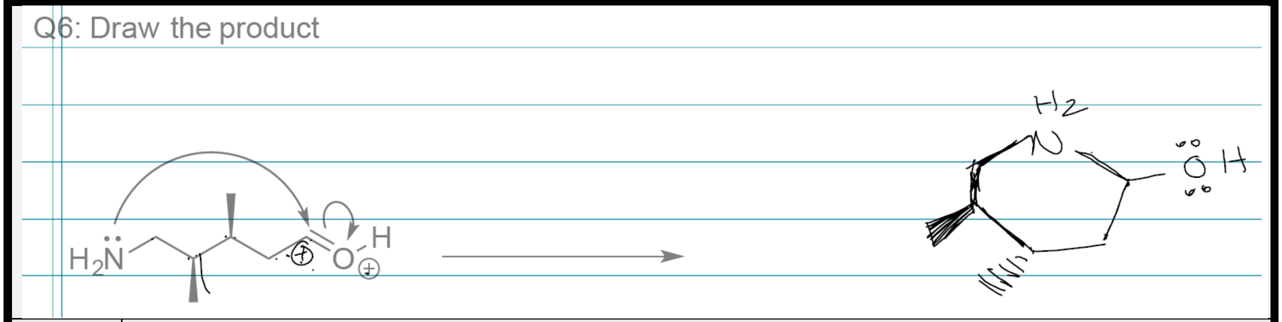
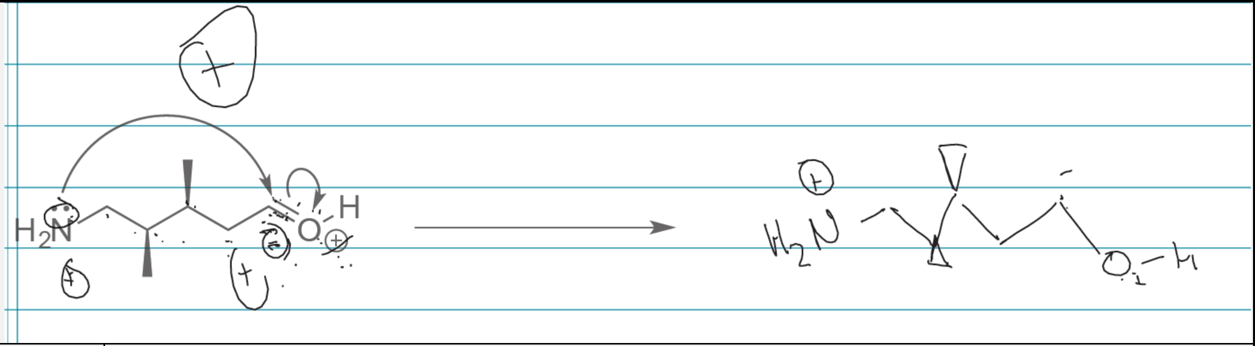
<tr><th colspan="2">Stepwise interpretation</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>Int:</td><td><i>“Okay, yeah um, did you think about the, and I, I think you probably just talked a little bit about this, so I was going to ask about the order of the arrows this time, if one happens before the other one or if they happen at the same time.”</i></td></tr>
<tr><td>#04:</td><td><i>“I think, yeah I think 'cause I saw that positive charge first I kind of figured, the elec- those- the electrons would move there first and then the second positive charge is made, and then that would- the electrons would move. Or else like the electron kind of doesn't really have a reason to move, there's no positive charge on the carbon… in the first place.”</i></td></tr>
<tr><th colspan="2">Stepwise interpretation</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>Int:</td><td><i>“So here is the question I have for this one, so does one of these arrows happen before the other one? Or do they happen at the same time.”</i></td></tr>
<tr><td>#08:</td><td><i>“Well this one has to occur beforehand because we can’t put another lone pair on there. like this doesn’t have a charge so I’m assuming this has a hydrogen bonded onto here m, so this of course has to happen first and I think this would like naturally just happen because of the. Bad charge here. When I say bad charge I mean not stable. Unstable charge. Um but I don’t know if this would naturally just occur. Like I guess it would, yeah it would have to, we cant just have a negative on this carbon by taking away like this bond and putting it on here. Um, nonono what am I saying. We cant just have a positive on this carbon by taking away the bond, like this would make a positive charge by taking away the negative bond um, so we have to put this on here I guess. So this would happen afterwards but this is more of a reaction towards what is happening here.”</i></td></tr>
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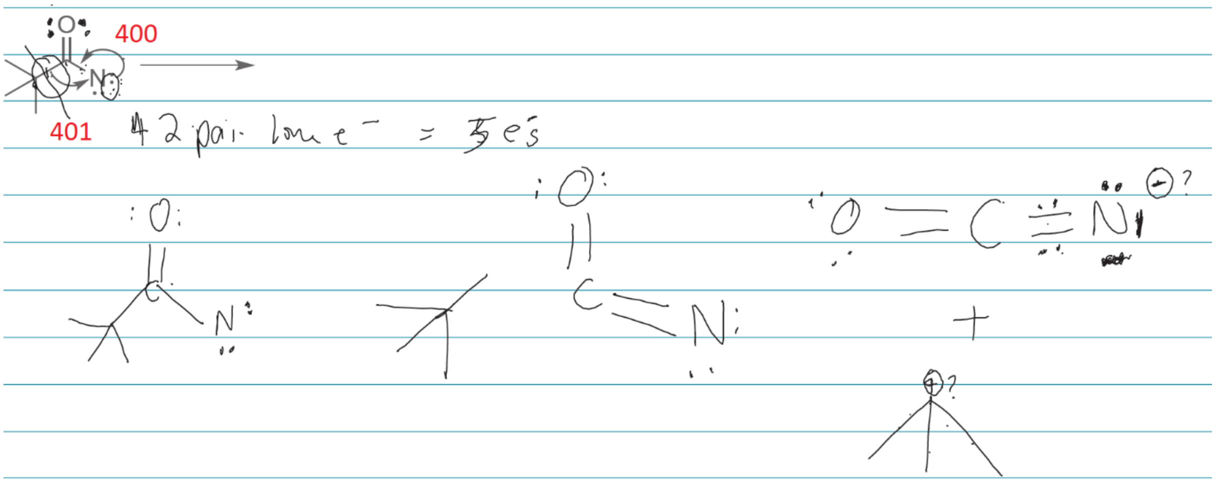
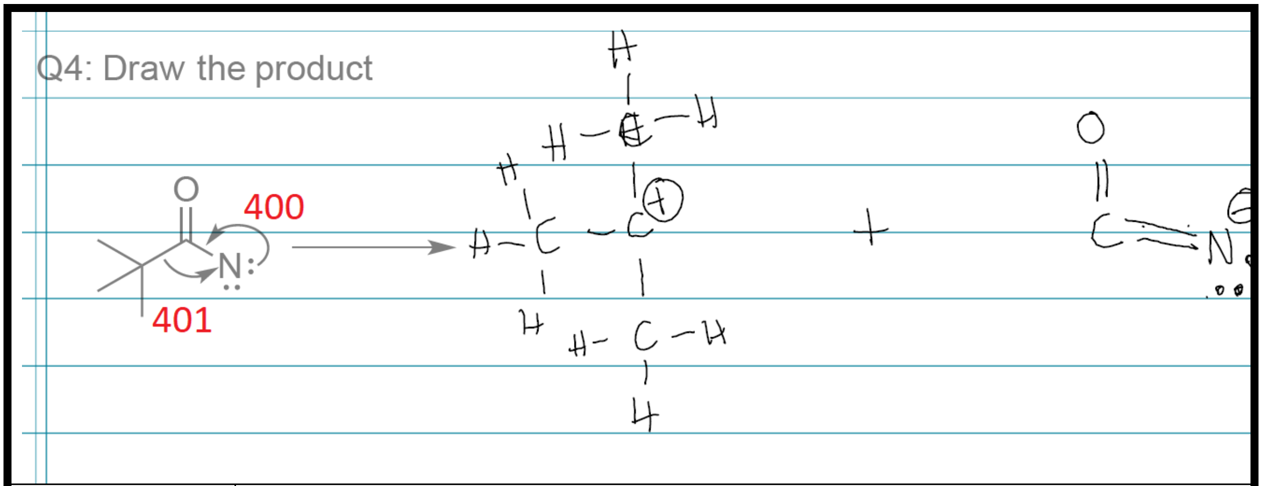
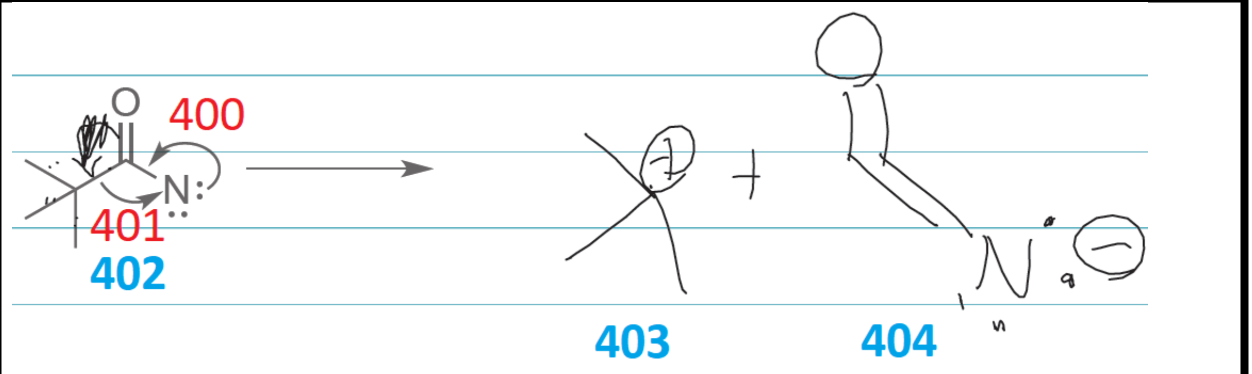
Appendix 21: All responses containing transplanted electrons for question 4

Question 4	
	
#01:	*"There's an arrow pointing from this side to this side too, so that means that. The bond is broken to put the electrons back to nitrogen […] so I think that this bond over here is broken and um and then it becomes two molecules. Because after the bond breaks. I don't know if the electrons go here. But the bond breaks um this part becomes separate from this part and so this part here with the oxygen and the nitrogen becomes one compound um the nitrogen the pairs of electrons here have an arrow pointing from them to the bond which means they are going to make a bond which means that carbon is going to have two double bonds which makes sense. Better than having the five bonds that I originally thought. So then the other compound the other section is just going to be chicken feet but that doesn't make sense so we're going to make it look nice, but I think there is going to be a charge here too, because I mean where does the electron go, right. Technically because it breaks I think similar to the second question it was, um the question with the um. Yeah this one because the electron breaks, you get half and half so one and one which is why they have charges."*
Int:	*"So those are your two products? You're trying to figure out if there's charge okay. How are you going to determine that."*
#01:	*"I think that because the bond is broken um between the two carbons here. Usually carbon would have a positive charge, because the electron is taken away from it [...]So here, nitrogen has four, four, two pair of lone e's. and because the bond is broken here it gets one more so that means a total of 5 e's and so there is one two. Two pairs. I will explain this. Um. The pair goes to make a bond here so then it's technically one. And it still has three. So three. Um and it's just one by itself, so it needs an extra electron to become more stable and so it has a negative charge because that one electron that it took is not originally the one electron."*

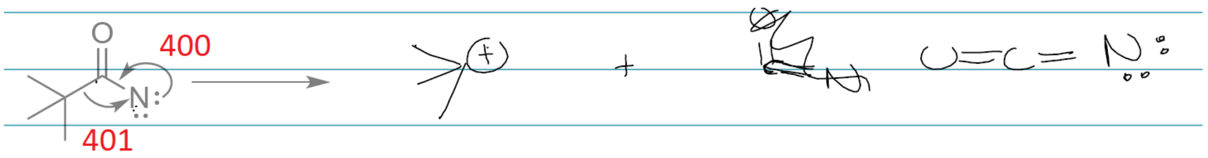


#02:	*"I'm guessing this is going to end up forming, I want to say a double bond with the N and the, the nitrogen and the carbon, just because the movement of the lone pairs to this bond here. But I'm not sure about this bond. I'm guessing that might be like a bond breaking between the two carbons here […] uhh. I don't know it's usual charge is. So I don't know like if it would be."*
Int:	*"what did you look on the periodic table that then help you to"*
#02:	*"I just count across, so like one two three four five. Five minus the number of electrons and pairs of electrons. Five minus six makes it negative one formal charge ."*
Int:	*"Okay, so how did you know there would be two products? How did you know that was going to happen?"*
#02:	*"I assumed because if there was an arrow from the bond here, that was moving towards the nitrogen. And so. I was assuming that the like the somehow the electrons in that would all transfer to here so then. There would be no electron sharing between them. So no bond between them."*

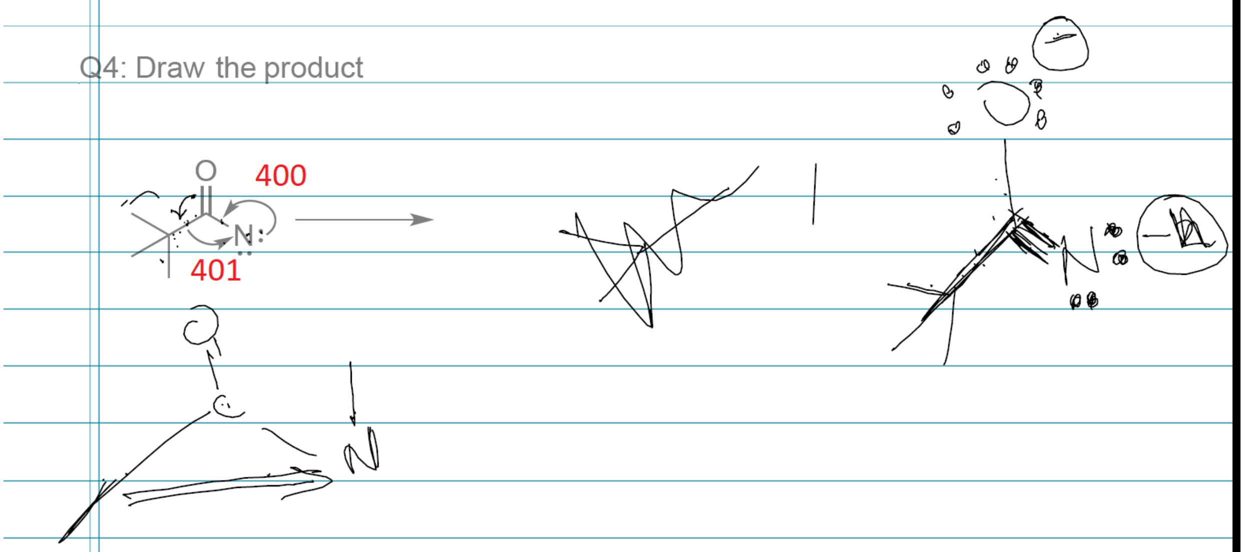


#03:	*"So it looks like this bond is breaking. Right here. And giving a lone pair of electrons to the nitrogen. So if I were to draw that. That would be this group by itself […] because this pair of electrons is going to the bond so it's forming another bond on top of there, so this basically forms these two. I'm just trying to think if there is a charge on that […] this carbon. Would have a positive charge. […] because before it had four things . Four bonds to it, so looking at the formal charge, four minus four is zero making it neutral, but since we broke the bond and gave it to the nitrogen, it has a positive charge , because it only has three bonds attached to it."*
Int:	*"Okay great, so tell me again how you know there are two products, how do you now those electrons are going to."*

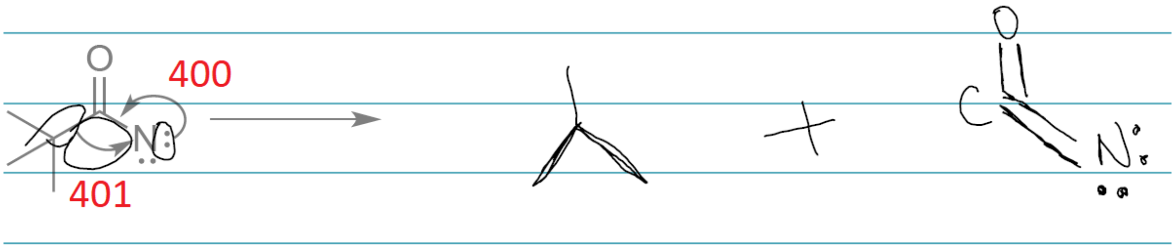
#03:	*"So this arrow shows to this bond is breaking because an arrow from a bond to an atom breaks the bond, giving that atom the two electrons. The lone pair of electrons. And since there's no other bond showing that they're attaching. like if it were to come back and attach mean that they are broken because that bond doesn't exist anymore because it's giving it's electrons to the nitrogen."*



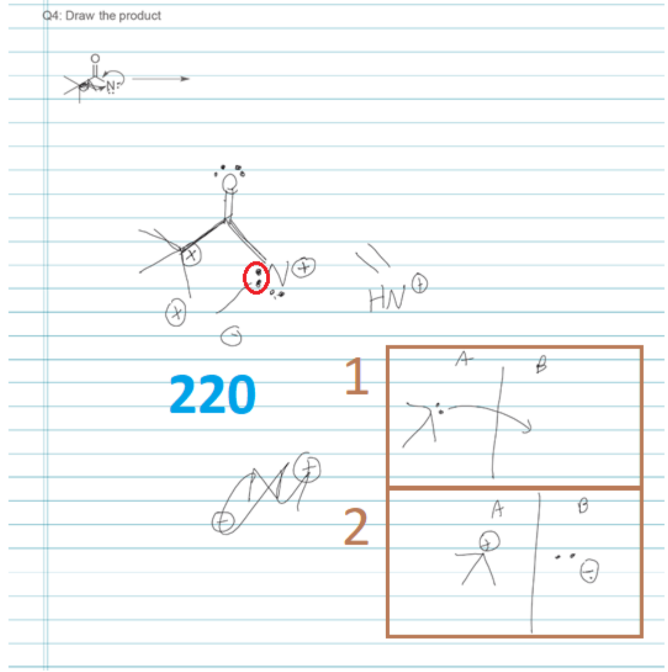
#04:	"This lone pair is being donated to the bond between the nitrogen and the carbon that has a double bond with the oxygen, so that would create a double bond. This bond […] Is being broken, I think yeah this bond is being broken where these electrons, or the electron- the lone pair the elec- or whatever the electrons between the carbon and the carbon are being donated to the nitrogen instead. So two molecules would be made, I think […], okay so this one would be left with four minus three, so positive charge , yeah positive charge so it would have, I think it'd have two molecules like this, yeah two molecules drawn like that."
Int:	"Okay, okay. How do you know that that bond is broken?"
#04:	"Because the two, uh, the arrow […] Dictates from the bond towards the nitrogen, rather than one of the actual atoms itself. So that dictates that that bond itself is actually being broken […] Uh in order to, well I guess give the electrons to the nitrogen […] Because the double headed arrow's pointing towards the nitrogen, yeah so th- yeah so the way there's actually pointing is where the electrons are going to be going to."



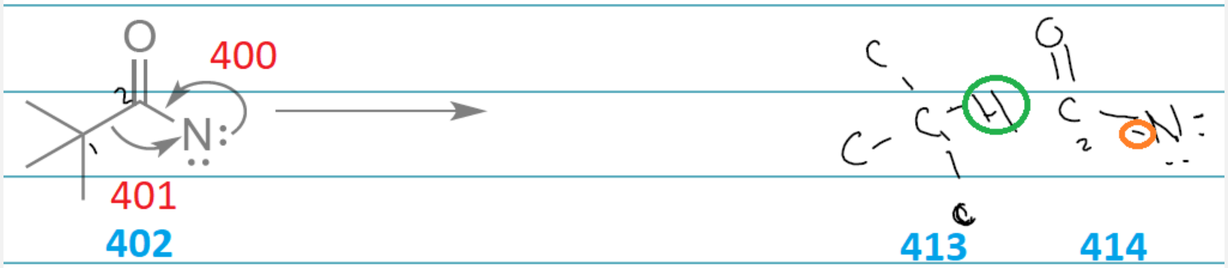
#05:	*"This carbon has like , yeah I don't I know I guess I can call it no charge either, so I guess like you wouldn't really want to touch it […]I think, okay maybe I'll move over to this side now, okay so it has this pair here and it's moving those now it would be a double bond […] Um, so I see this arrow is pointing to this, the nitrogen […] And it's showing, not really sure what it's showing, I guess it wants to put like (...) two more electrons there or something […] So I think maybe this happens first, so like this double bond first, like this has to uh well it's not really happening, but I feel like […] Like I feel like um this oxygen here has to give it one of its bonds here*

	so that the electrons can come from here to the nitrogen, and then the nitrogen can give its electrons to here, like it's a bit of a full circle thing? Um, yeah, and I'm still not sure if you can just break this bond here an- to do that but I don't know what else you would do.”
Int:	*“Okay, is that your final structure?”*
#05:	*“I think so […] It's got a lot of charges […] Um it tells me that it might not be right because you usually want something with like the least amount of charges […] I don't know, I find it weird 'cause kay so if I wanted to get rid of these charges then I would be pretty much be undoing this […] Okay yeah, I'm not really sure.”*
Question 4	
	
#07:	*“Um, this left side arrow [Arrow 56] here it must attach this bond here and usually when that happens the bond’s broken so I guess the two compounds separated [Molecules 57 and 58] and then so you have to make two different things so this left side compound [Molecule 57] is just this methyl- 3 methyl something like that- 3 methyl substituents. And then the second one, the elect-these electrons [Arrow 59] move to form another double bond um and then the electrons from, the electrons from that- the bond broke off and then connected to nitrogen again creating another double bond… [whispers] is that right… and then so the carbon is full; it has a double bond with the oxygen, double bond with the nitrogen. […] Hmm, the curved arrow, the first on the bottom [Arrow 56] it mo- definitely moved the bond either the bond... I might have drawn this incorrectly or not sure. But it moved the bond- broke the bond and the bond became an electron and attached to the nitrogen [Molecule 58]. And the- this large higher curved arrow [Arrow 59] took the electrons and create- turned into a bond that connect to the central carbon atom. […] Hmm, not really I mean it was pretty straight forward. The bond broke [Arrow 56] and then you move electrons over to create two compounds [Molecules 57 and 58].”*

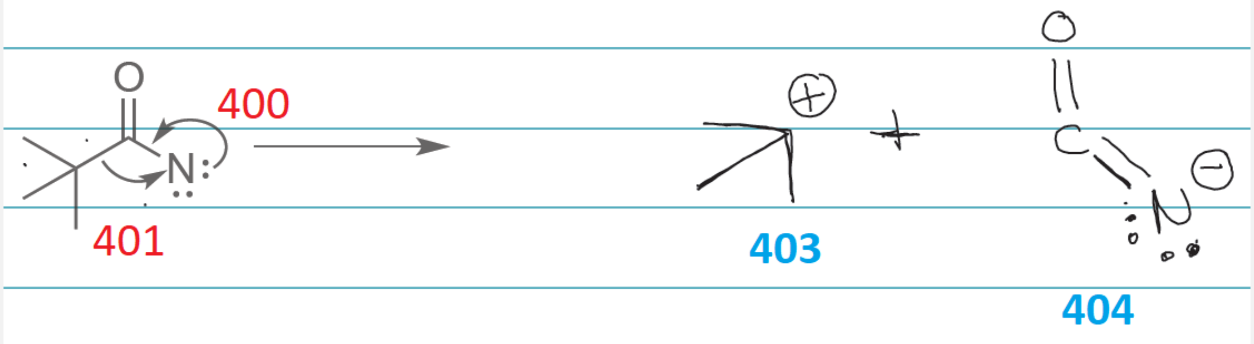
Question 4



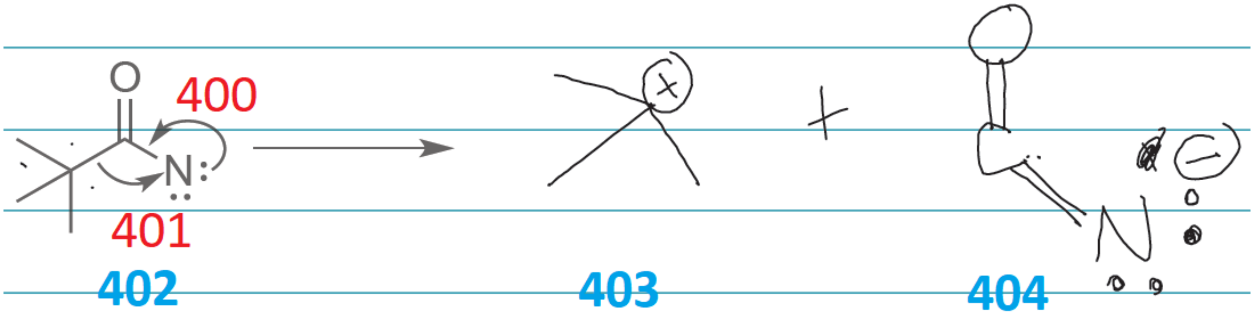
#09:	*“I want to say that that's a double bond right off the bat , and then from here, hmm so that's from a bond to the nitrogen and that's going to give it two electrons I'm thinking, and then this is probably going to be left with a negative charge […] so because the electrons are going away from the nitrogen and forming this double bond […] It also is gaining electrons, so I'm not sure if, if you, this side gains, so this is side A and side B […] So then A loses the electrons and becomes positive and B gains them and becomes negative.”*



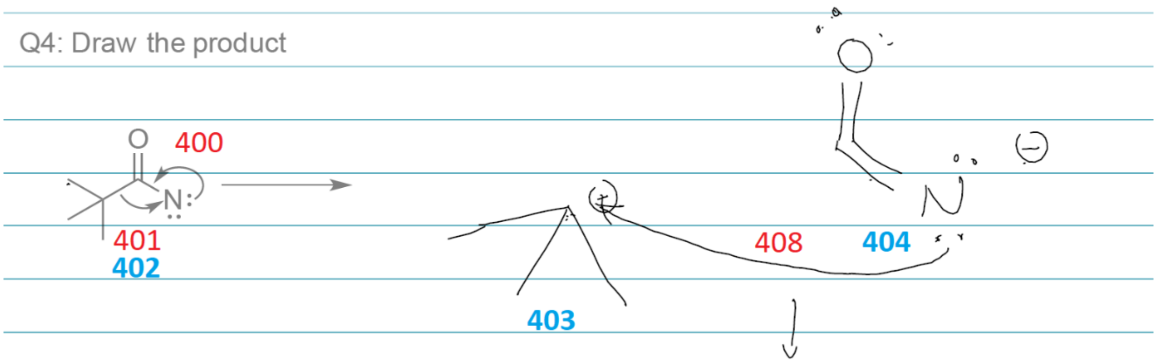
#11:	*“**Well there is an arrow** [Arrow 400] **pointing from a lone pair to a single carbon nitrogen bond** and **there is a carbon-carbon single pointing to the nitrogen** [arrow 401]. […] **Um, I think one bond is being broken and one is being formed**. […] Um, so I guess one half of it, still trying to figure out what the other half does. **I want to say the bond breaks then the electron, the extra electron goes to the nitrogen to fill it again**.”*



#12:	*“Um, okay so well the first part's the same, (...drawing)* ***um and then so this bond is moving onto the um, the nitrogen*** *[…]* ***So that means there's nothing connecting- it breaks into two molecules*** *Um so you have your double, your carbon double bonded to the oxygen. And then um, well you can see that a double bond is forming […] Between the nitrogen and the carbon (...drawing), put the plus, um and then the nitrogen, it loses a lone pair but then it also gains one. (...drawing) so it's like that, um and then nitrogen I think it's five valence electrons, actually […]and then this case you have um one, two, three, four, five, six um electrons around it , so that has a negative charge, um even though it previously also, no previously it was fine. Um (...) and I think that's it, but something, oh this carbon has a positive charge now. Um because it lost an electron and it didn't gain any more.”*
Int:	*“Yeah so tell me, um you said the first, one of the first things you said is that bond moves onto the nitrogen, so how do you, how do you know that that happens, and uh how does it form that lone pair?”*
#12:	*“you know that it forms um the lone pair because it's showing it onto the nitrogen instead of showing it, like if it were to show it to the bond then that means the bond is forming, but since it's showing that the bond, like the back of the arrow's on the bond and the arrow head is on the nitrogen , it means that the um, well the electrons are moving on to the hydrogen [Sic], not between the carbon and the nitrogen because if you look at the arrow um that's showing you the electrons onto th- like to the bond Um it's showing it to the bond so it means it's between them ... Um, so that's how I knew that it was um a lone pair and not a bond, like another bond between then carbon and nitrogen.”*

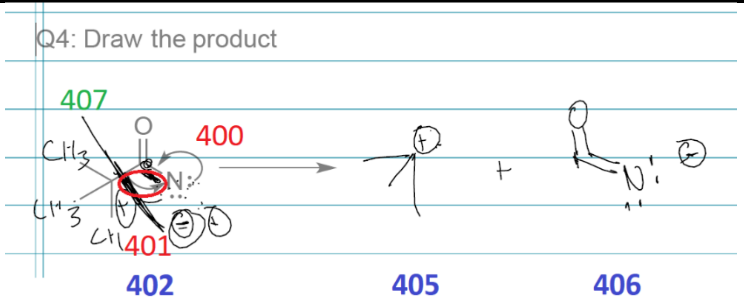


#13:	*“Okay um so (...) the nitrogen is giving electrons to this bond, which will, which would normally form a, so that would form a double bond? And, but this bond is breaking and giving electrons to the nitrogen, so I'm so a bonds breaking so I'm thinking we're gonna have two products. […] it looks like it's gonna have a double bond to a nitrogen which would fulfill its octet and this nitrogen is still gonna have two lone pairs however, so originally it have a lone pair to this bond […] And then it got a pair of electrons from this bond so that's gonna give it a negative charge […]And this carbon here though only has three bonds so I'm gonna give it a positive charge.”*

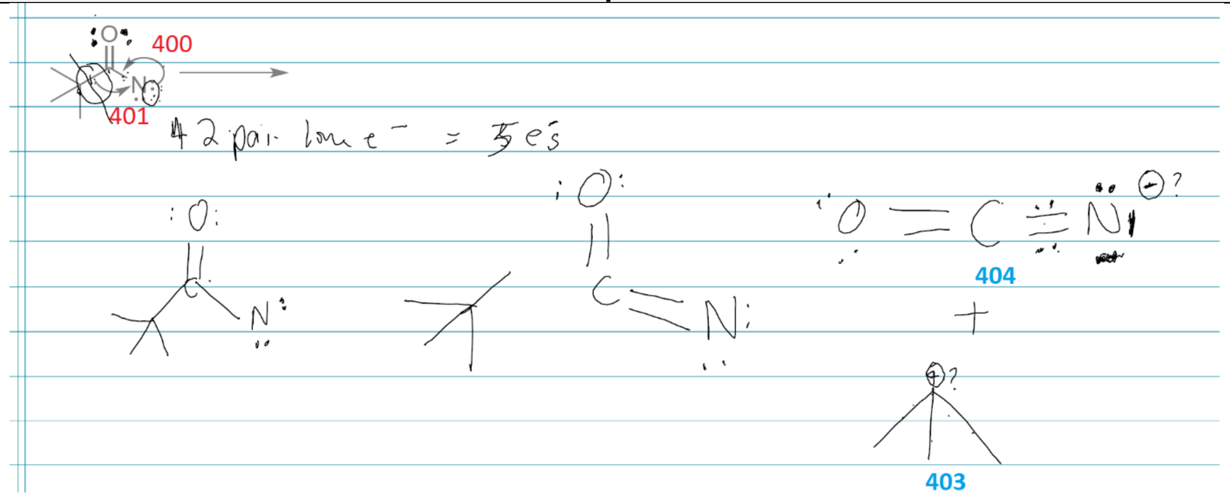


#06:	*"This uh bond here is going to this nitrogen […] Presumably to use those two electrons for a new lone pair […] So because this single bond is leaving um I'm thinking that it should be two products ? Because this bond is being broken […] And one, two, three, so the carbon is at least happy, uh 'cause it has the four bonds coming off of it, the oxygen doesn't care then the nitrogen is one, two, three, four, five, six yeah the uh the nitrogen is negative , I drew that and this carbon here as positive […] So I'm not s- entirely satisfied with it […] Um, I'm well just- the way interpreted it here, the way I have it drawn here, um it seems there there's loose ends if you will […]There's um, like this is left positive, this is left negative and it makes it seem much more like an intermediate […]Than a final product […] from how I interpreted this, this seems like an intermediate, so what I think from what I found, what should happen is this nitrogen bonds with that and then it's, goes to become uh right double bonded into the nitrogen, the nitrogen has a single lone pair coming off of it, and then that's bonded to the three methyl groups […]And now it's, this carbon's happy, this oxygen's happy, one, two, three, four, five, then the nitrogen's neutral, this carbon has the four bonds so it's happy and it seems like that should be the final product? […] I'm thinking maybe this would be right, 'cause I'm thinking maybe I interpreted this wrong and this bond should've just gone to the nitrogen right away rather than me given the electrons […] Because this looks like what could've happened here 'cause this bond just goes here, so now it's bonded to it, it has a single pair 'cause it gave up a pair and then yeah, okay I'm more confident in my answer now. […] Um, well initially I assumed it was the electrons just because uh all I've seen for arrow moving so far, arrow pushing, has just been um just electrons, like electron here moves to here, here moves to here so that's why I immediately thought that it was electron movement uh from this single bond and whenever we moved electrons with double bonds it was always from that one, one of the bonds of the double bonds that those two electrons are now here, or wherever it gets moved to […]Um so now, now just looking at this, we've never looked too much at uh mechanisms where you have uh a single bond and you just move the single bond here immediately […] Um so that's why- now but now looking at it, I can see that the electron movement will result in that single bond moving […] So maybe that's what this mechanism was demonstrating […] From the very start and I just missed it […] And I just did the intermediate."*
Int:	*"Okay, do you think if this were happening that these intermediates would be deformed first, or do you think it just moves from here to here?"*
#06:	*"Um, I would assume that the um electrons here would want to move here first, but maybe again the theory of intermediates and all that, I'm not uh super strict,*

	I'm not sure um, I'm not comfortable with, I'm not super in- we're not in depth in that in class yet. […] But I'm not sure, maybe I would assume that the electrons from this bond would move here first, but then actually, probably not, well mmm, I would- maybe s- I would say so yes, that just because um this group here has to be separated from the whole group first […] Before it can, before it can re-bond to the nitrogen I'm gonna- so I'm gonna say yes, this intermediate would have to take place, um yeah just because this group needs to be uh taken away from this carbon basically, before it can bond to the nitrogen because I- I've never really seen anything where the uh a single bond just pivots to another molecule."
Question 1	
#06:	*"'Cause it's all just movin- moving electrons … That's what the arrows show, it's just moving electrons around, so uh it's all about how the electrons want to move, so really basically just negative to positive."*

Question 2 – Transplanting is not possible	
#08:	*"**From what I understand like so like I can't just like, just pluck these electrons off and just like glue them on here** […] **yeah, you can't take them off of somewhere they have to move through** […] like they're not actual atoms they're subatomic particles so like **they have move through other atoms**"*
Question 4 – Transplanting is not possible	
	
#08:	*"Oh okay. So here first off I guess **we should look at this bottom arrow** [Arrow 401 circled in red]. **Which is actually breaking a bond here**. **So we actually break these apart** [Black line labeled 407]. **So then this would become just a. methyl group** [Molecule 405]. And **since we have the electrons coming here** […] Like we have the end of the arrow would indicate that this has a positive area. Like this has a positive charge [positive charge on molecule 405 drawn by participant #08], and this would gain a negative charge here [negative charge on molecule 406 drawn by participant #08] […] so then here we have a lone pair [arrow 36] coming off of the nitrogen. To make a double bond on this molecule **um, I guess it's just something we learned. You can't really take electrons out of a bond and still have the bond be there**. **cause like a single bond is two electrons and whenever you are moving electrons, you are always moving two**. You can't move one at a time. **And so you can't take one electron out and have half a bond. so you need to like, break the full bond apart** [Black line labeled 407] **to get those electrons out to make the lone pair on the N** [Molecule 406]."*

Appendix 22: All responses containing a positive charge and negative charge on molecules 405 and 406 respectively for question 4

<table>
<tr><th colspan="2">Participant #01</th></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>#01:</td><td><i>“There’s an arrow [Arrow 401] pointing from this side to this side too, so that means that. The bond is broken to put the electrons back to nitrogen […]: so I think that this bond over here is broken and um and then it becomes two molecules. Because after the bond breaks. I don’t know if the electrons go here. But the bond breaks um this part becomes separate from this part and so this part here with the oxygen and the nitrogen becomes one compound [Molecule 404] um the nitrogen the pairs of electrons here have an arrow [Arrow 400] pointing from them to the bond which means they are going to make a bond which means that carbon is going to have two double bonds which makes sens. Better than having the five bonds that I originally thought. So then the other compound the other section is just going to be chicken feet [Molecule 403] but that doesn’t make sense so we’re going to make it look nice, but I think there is going to be a charge here too, because I mean where does the electron go, right. Technically because it breaks I think similar to the second question it was, um the question with the um. Yeah this one because the electron breaks, you get half and half so one and one which is why they have charges.</i>”</td></tr>
<tr><td>Int:</td><td><i>“So those are your two products? You’re trying to figure out if there’s charge okay. How are you going to determine that?”</i></td></tr>
<tr><td>#01:</td><td><i>“I think that because the bond is broken [arrow 401] um between the two carbons here. Usually carbon would have a positive charge, because the electron is taken away from it [...]So here, nitrogen has four, four, two pair of lone e’s. and because the bond is broken here it gets one more so that means a total of 5 e’s and so there is one two. Two pairs. I will explain this. Um. The pair goes to make a bond here so then it’s technically one. And it still has three. So three. Um and it’s just one by itself, so it needs an extra electron to become more stable and so it has a negative charge because that one electron that it took is not originally the one electron.”</i></td></tr>
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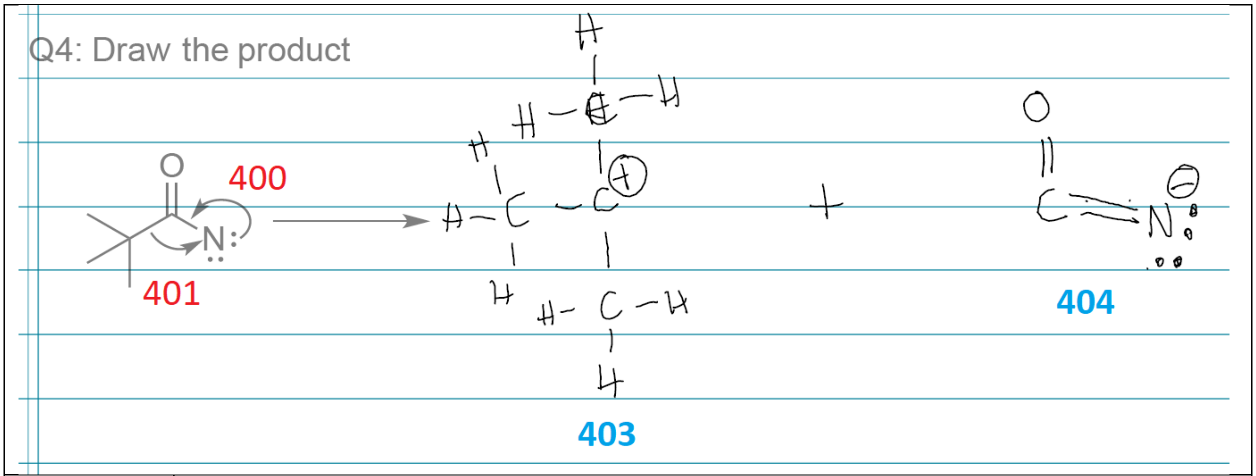
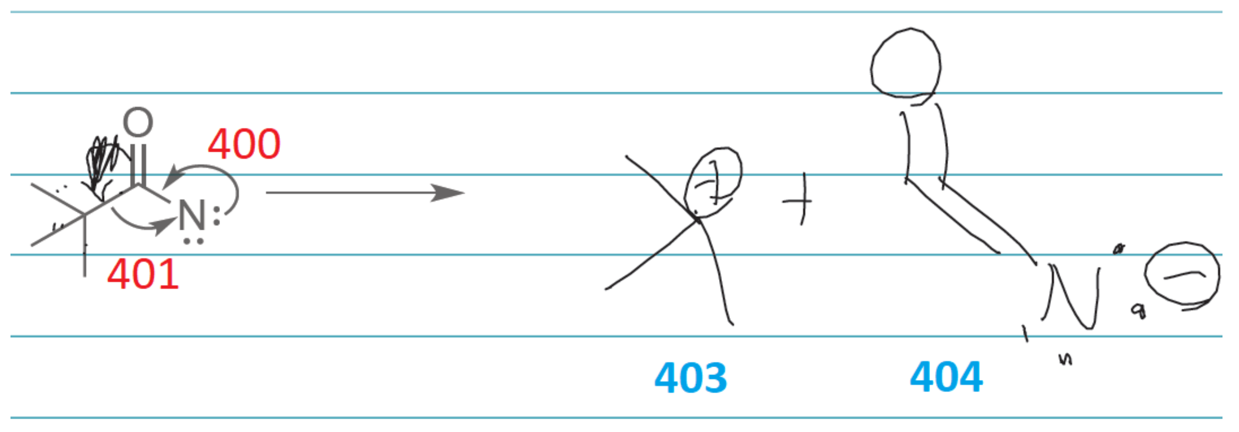
Participant #02



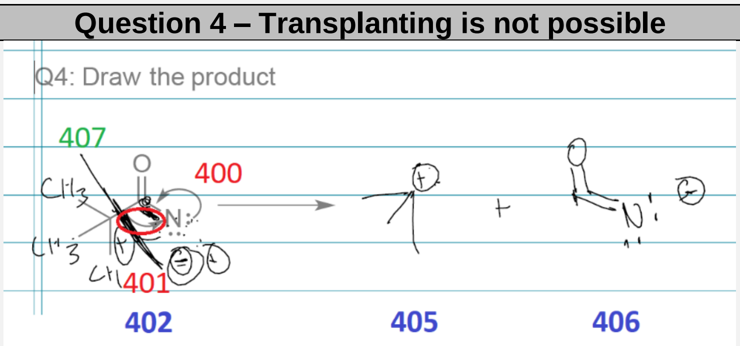
#02:	*"I'm guessing this is going to end up forming, I want to say a double bond with the N [Arrow 400] and the, the nitrogen and the carbon, just because the movement of the lone pairs to this bond here. But I'm not sure about this bond. I'm guessing that might be like a bond breaking between the two carbons here [Arrow 401] […] uhh. I don't know it's usual charge is. So I don't know like if it would be."*
Int:	*"what did you look on the periodic table that then help you to"*
#02:	*"I just count across, so like one two three four five. Five minus the number of electrons and pairs of electrons. Five minus six makes it negative one formal charge [Molecule 404]."*
Int:	*"Okay, so how did you know there would be two products? How did you know that was going to happen?"*
#02:	*"**I assumed because if there was an arrow** [Arrow 401] **from the bond here**, **that was moving towards the nitrogen**. And so. I was assuming that the like the **somehow the electrons in that would all transfer to here** [Molecule 404] so then. There would be no electron sharing between them. So no bond between them."*

Participant #03

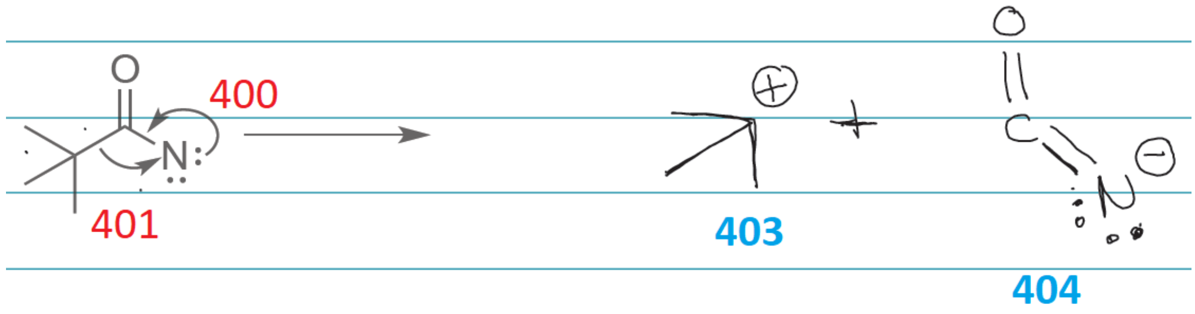


#03:	*"**So it looks like this bond is breaking. Right here. And giving a lone pair of electrons to the nitrogen** [Arrow 401]. So if I were to draw that. That would be this group by itself […] because this pair of electrons is going to the bond [Arrow 400] so it's forming another bond on top of there, so this basically forms these two. I'm just trying to think if there is a charge on that […] this carbon. Would have a*

	positive charge [Molecule 403]. […] because before it had four things Four bonds to it, so looking at the formal charge, four minus four is zero making it neutral, but since we broke the bond and gave it to the nitrogen, it has a positive charge [Molecule 404], because it only has three bonds attached to it.
Int:	*“okay great, so tell me again how you know there are two products, how do you now those electrons are going to.”*
#03:	*“So this arrow [Arrow 401] shows to this bond is breaking because an arrow from a bond to an atom breaks the bond, giving that atom the two electrons [Molecule 404]. The lone pair of electrons. And since there’s no other bond showing that they’re attaching. like if it were to come back and attach mean that they are broken because that bond doesn’t exist anymore because it’s giving it’s electrons to the nitrogen.”*

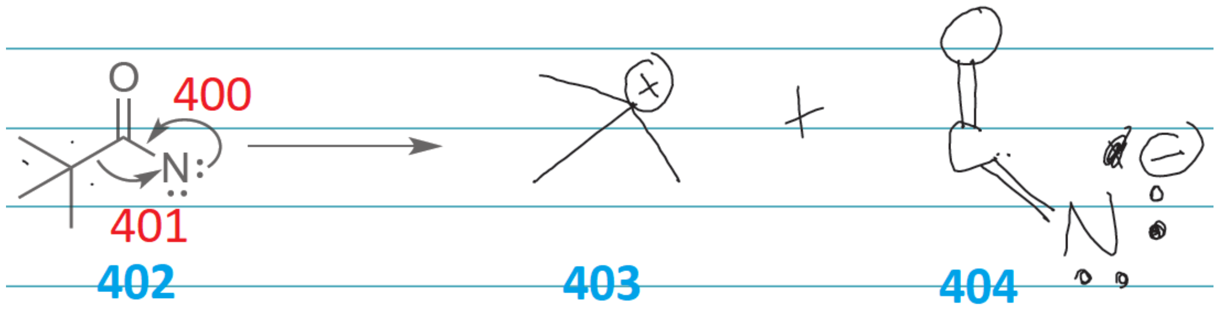
Participant #08	
Question 2 – Transplanting is not possible	
#08:	*“**From what I understand like so like I can’t just like, just pluck these electrons off and just like glue them on here** […] **yeah, you can’t take them off of somewhere they have to move through** […] like they’re not actual atoms they’re subatomic particles so like **they have move through other atoms**”*
Question 4 – Transplanting is not possible	
	
#08:	*“Oh okay. So here first off I guess **we should look at this bottom arrow*** [Arrow 401 circled in red]. ***Which is actually breaking a bond here***. ***So we actually break these apart*** [Black line labeled 407]. ***So then this would become just a. methyl group** [Molecule 405]. And **since we have the electrons coming here** […]* Like we have the end of the arrow would indicate that this has a positive area. Like this has a positive charge [positive charge on molecule 405 drawn by participant #08], and this would gain a negative charge here [negative charge on molecule 406 drawn by participant #08] […] so then here we have a lone pair [arrow 36] coming off of the nitrogen. To make a double bond on this molecule ***um, I guess it’s just something we learned. You can’t really take electrons out of a bond and still have the bond be there***. ***cause like a single bond is two electrons and whenever you are moving electrons, you are always moving two***. *You can’t move one at a time.* ***And so you can’t take one electron out and have half a bond. so you need to like, break the full bond apart*** [Black line labeled 407] ***to get those electrons out to make the lone pair on the N** [Molecule 406].”*

Participant #12



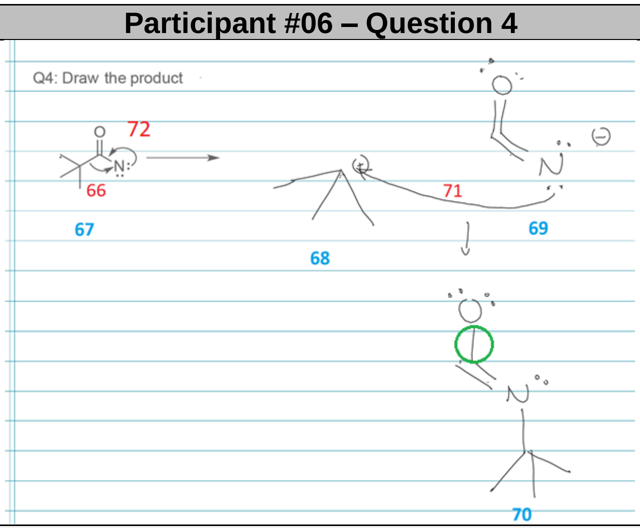
#12:	*“Um, okay so well the first part's the same, (...drawing)* ***um and then so this bond is moving onto the um, the nitrogen*** *[Arrow 401] […]* ***So that means there's nothing connecting- it breaks into two molecules*** *[Molecules 403 & 404]. Um so you have your double, your carbon double bonded to the oxygen. And then um, well you can see that a double bond is forming […] Between the nitrogen and the carbon [Arrow 400] (...drawing), put the plus, um and then the nitrogen, it loses a lone pair but then it also gains one. (...drawing) so it's like that, um and then nitrogen I think it's five valence electrons, actually […]and then this case you have um one, two, three, four, five, six um electrons around it [Molecule 404], so that has a negative charge, um even though it previously also, no previously it was fine. Um (...) and I think that's it, but something, oh this carbon [Molecule 403] has a positive charge now. Um because it lost an electron and it didn't gain any more.”*
Int:	*“Yeah so tell me, um you said the first, one of the first things you said is that bond moves onto the nitrogen, so how do you, how do you know that that happens, and uh how does it form that lone pair?”*
#12:	*“you know that it forms um the lone pair because it's showing it onto the nitrogen instead of showing it, like if it were to show it to the bond then that means the bond is forming, but since it's showing that the bond, like the back of the arrow's on the bond and the arrow head is on the nitrogen [Arrow 401], it means that the um, well the electrons are moving on to the hydrogen [Sic], not between the carbon and the nitrogen because if you look at the arrow um that's showing you the electrons onto th- like to the bond .. Um it's showing it to the bond so it means it's between them ... Um, so that's how I knew that it was um a lone pair and not a bond, like another bond between then carbon and nitrogen.”*

Participant #13



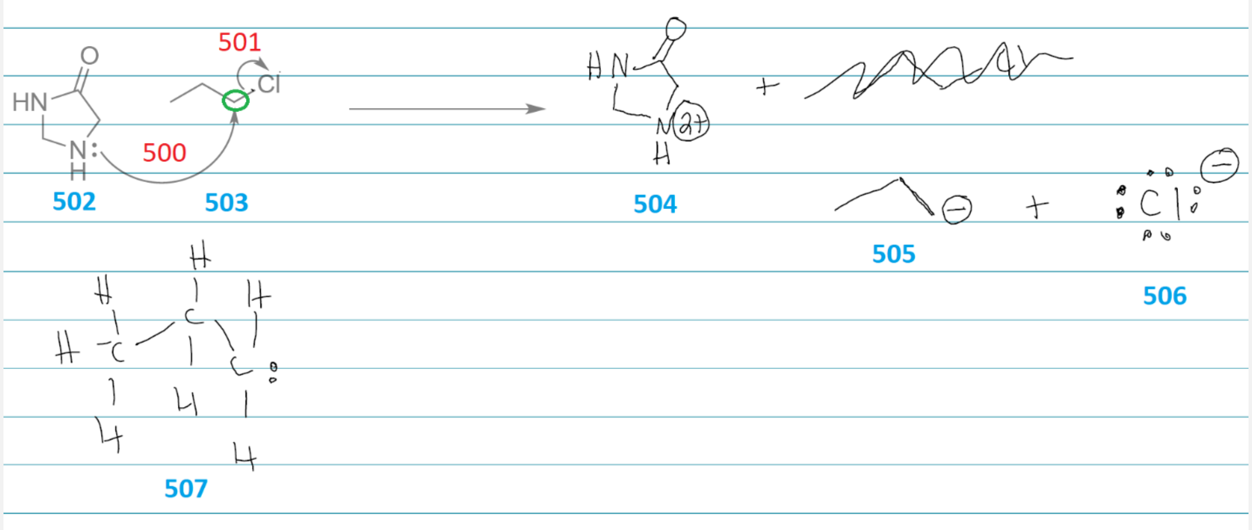
#13:	*“Okay um so (...) the nitrogen is giving electrons to this bond [Arrow 400], which will, which would normally form a, so that would form a double bond?* ***And, but this bond is breaking and giving electrons to the nitrogen*** *[Arrow 401], so I'm so a bonds breaking so I'm thinking we're gonna have two products. […] it looks like it's gonna have a double bond to a nitrogen which would fulfill its octet and this nitrogen is still gonna have two lone pairs however, so originally it have a lone pair to this bond […] And then it got a pair of electrons from this bond so that's gonna give it a negative charge [Molecule 404]*

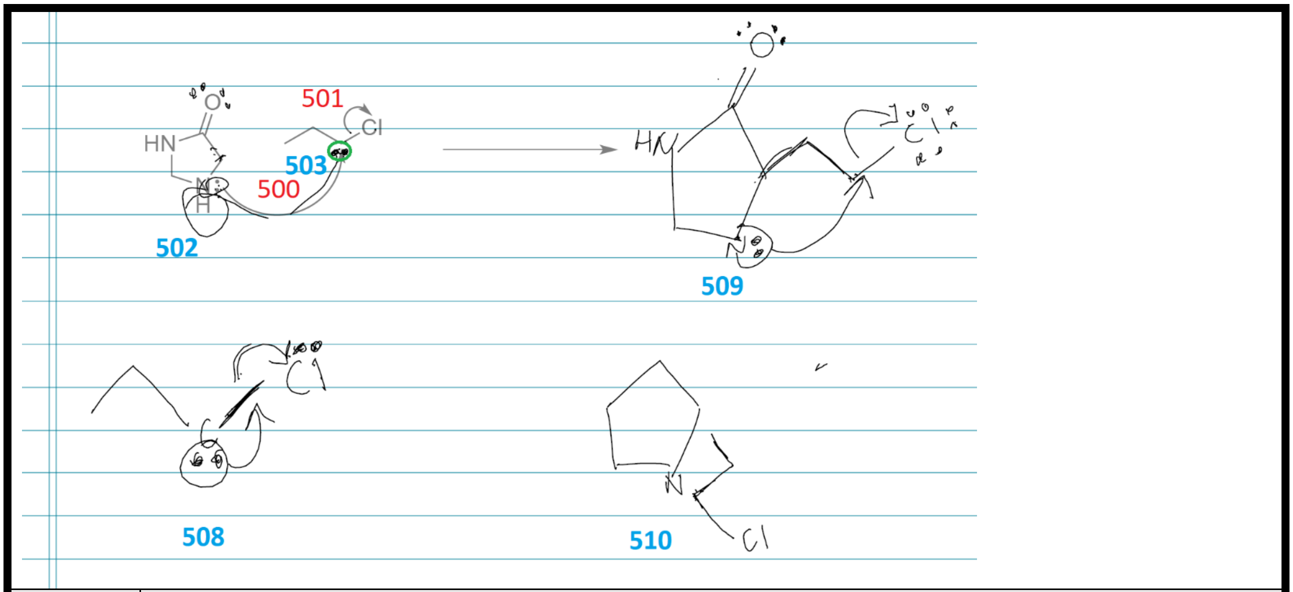
	[…]And this carbon here though only has three bonds so I'm gonna give it a positive charge [Molecule 403].”

Participant #06 – Question 4	
	
#06:	*“This uh bond here is going to this nitrogen [Arrow 401] […] Presumably to use those two electrons for a new lone pair […] So because this single bond is leaving um I'm thinking that it should be two products [Molecules 403 and 404]? Because this bond is being broken […] And one, two, three, so the carbon is at least happy, uh 'cause it has the four bonds coming off of it, the oxygen doesn't care then the nitrogen is one, two, three, four, five, six yeah the uh the nitrogen is negative [molecule 404], I drew that and this carbon here as positive [molecule 403] […] So I'm not s- entirely satisfied with it […] Um, I'm well just- the way interpreted it here, the way I have it drawn here, um it seems there there's loose ends if you will […]There's um, like this is left positive [molecule 403], this is left negative [molecule 403] and it makes it seem much more like an intermediate […]Than a final product […] from how I interpreted this, this seems like an intermediate, so what I think from what I found, what should happen is this nitrogen bonds with that and then it's, goes to become uh right double bonded into the nitrogen, the nitrogen has a single lone pair coming off of it, and then that's bonded to the three methyl groups […]And now it's, this carbon's happy, this oxygen's happy, one, two, three, four, five, then the nitrogen's neutral, this carbon has the four bonds so it's happy and it seems like that should be the final product [molecule 411]? […] I'm thinking maybe this would be right, 'cause I'm thinking maybe I interpreted this wrong and this bond should've just gone to the nitrogen right away rather than me given the electrons […] Because this looks like what could've happened here 'cause this bond just goes here, so now it's bonded to it, it has a single pair 'cause it gave up a pair and then yeah, okay I'm more confident in my answer now. […] Um, well initially I assumed it was the electrons just because uh all I've seen for arrow moving so far, arrow pushing, has just been um just electrons, like electron here moves to here, here moves to here so that's why I immediately thought that it was electron movement uh from this single bond and whenever we moved electrons with double bonds it was always from that one, one of the bonds of the double bonds that those two electrons are now here, or wherever it gets moved to […]Um so now, now just looking at this, we've never looked too much at uh mechanisms where you have uh a single bond and you just move the single bond here immediately […] Um so that's why- now but now looking at it, I can see that the electron movement will result in that single bond moving […] So maybe that's what this mechanism was*

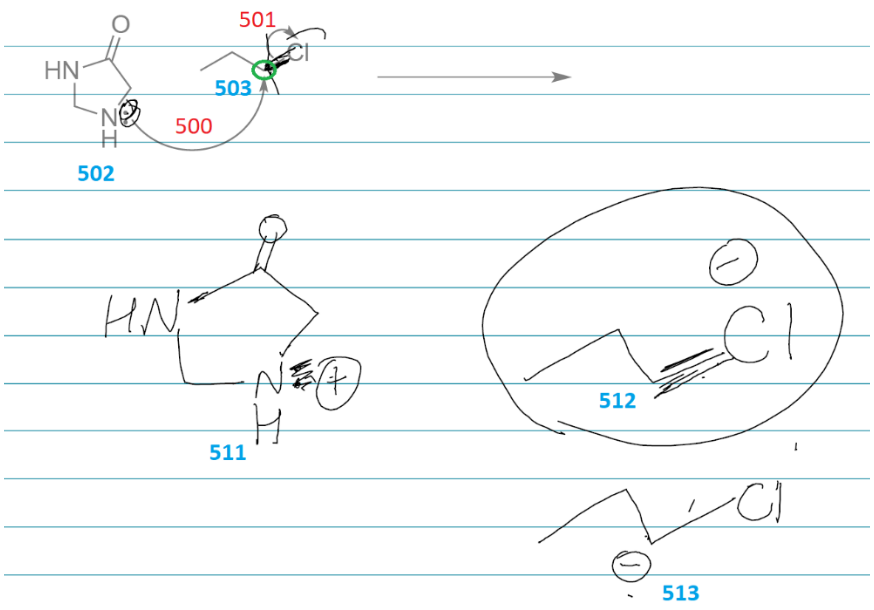
	demonstrating […] From the very start and I just missed it […] And I just did the intermediate.”
Int:	*“Okay, do you think if this were happening that these intermediates would be deformed first, or do you think it just moves from here to here?”*
#06:	*“Um, I would assume that the um electrons here would want to move here first, but maybe again the theory of intermediates and all that, I'm not uh super strict, I'm not sure um, I'm not comfortable with, I'm not super in- we're not in depth in that in class yet. […] But I'm not sure, maybe I would assume that the electrons from this bond would move here first, but then actually, probably not, well mmm, I would- maybe s- I would say so yes, that just because um this group here has to be separated from the whole group first […] Before it can, before it can re-bond to the nitrogen [arrow 410]. I'm gonna- so I'm gonna say yes, this intermediate [molecules 403 and 404] would have to take place, um yeah just because this group needs to be uh taken away from this carbon basically, before it can bond to the nitrogen because I- I've never really seen anything where the uh a single bond just pivots to another molecule.”*
Question 1	
#06:	*“'Cause it's all just movin- moving electrons … That's what the arrows show, it's just moving electrons around, so uh it's all about how the electrons want to move, so really basically just negative to positive.”*

Appendix 23: All responses containing transplanted electrons from the nitrogen atom onto the carbon atom for questions 5 and 6

Question 5	
	
Int:	*“Talk me through how you knew the electrons were going to be transferred. Or this lone pair is going to be on this carbon [circled in green on molecule 503].”*
#02:	***“Uhh. Well From the arrow*** *[Arrow 500].* ***The lone pair from the nitrogen are going to be transferred to that carbon specific.*** *And I was contemplating if that was at the bottom. But I’m pretty sure if it made a double bond then the nitrogen, the electrons would be pointing. The arrow here would be pointing towards the bond.”*
Int:	*“What told you here that any bonds were being broken or formed. I don’t know if we have any bonds forming.”*
#02:	***“I don’t see any bonds forming, but breaking here was the bond here from this arrow*** *[Arrow 501]* ***to this chlorine****. And yeah. That would have made it.* ***Broken the bond instead of the electrons being on the carbon will be on the chlorine*** *[Molecule 506].”*

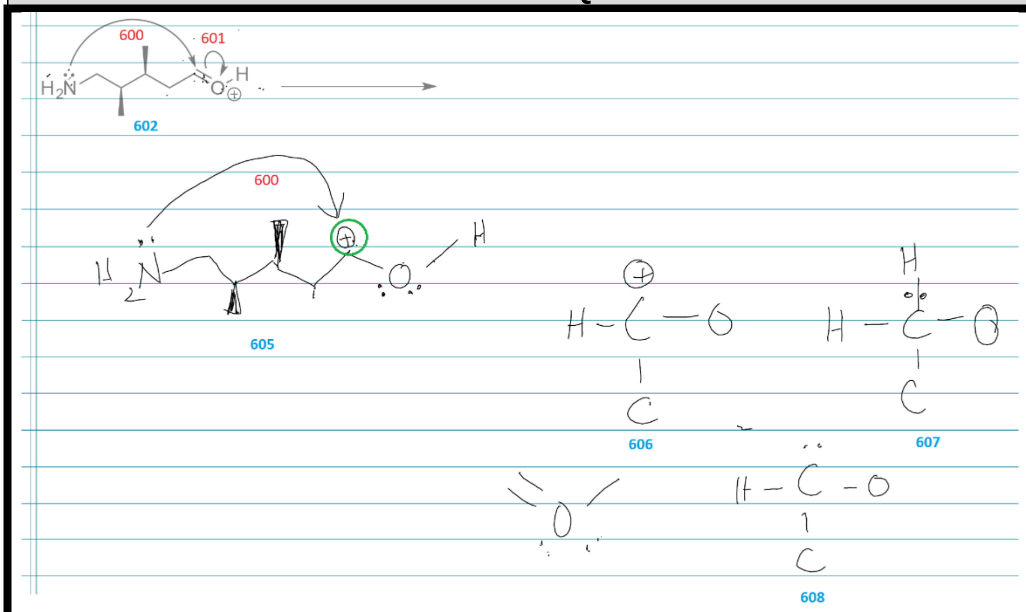


Int:	“Yeah, yeah um what did the arrows, the curved arrows here tell you for this problem?”
#05:	“**Um so it told me, like that it was pretty obvious but the electrons here** [Arrow 500] **were gonna go um onto this carbon here** [Green circle on molecule 503] […] **And it made me think that maybe, okay it was already full and that this carb- like that's why they were gonna take the electrons** [Arrow 501] **and put it onto the chlorine**, but it was kinda confusing at the same time 'cause um, that would mean that originally chlorine would only have like four electrons […] Which I don't think would happen**, so I'm not too sure what it's really talking about there […] Yeah like I don't know** […] **How you can just put those electrons there** (laughs).”

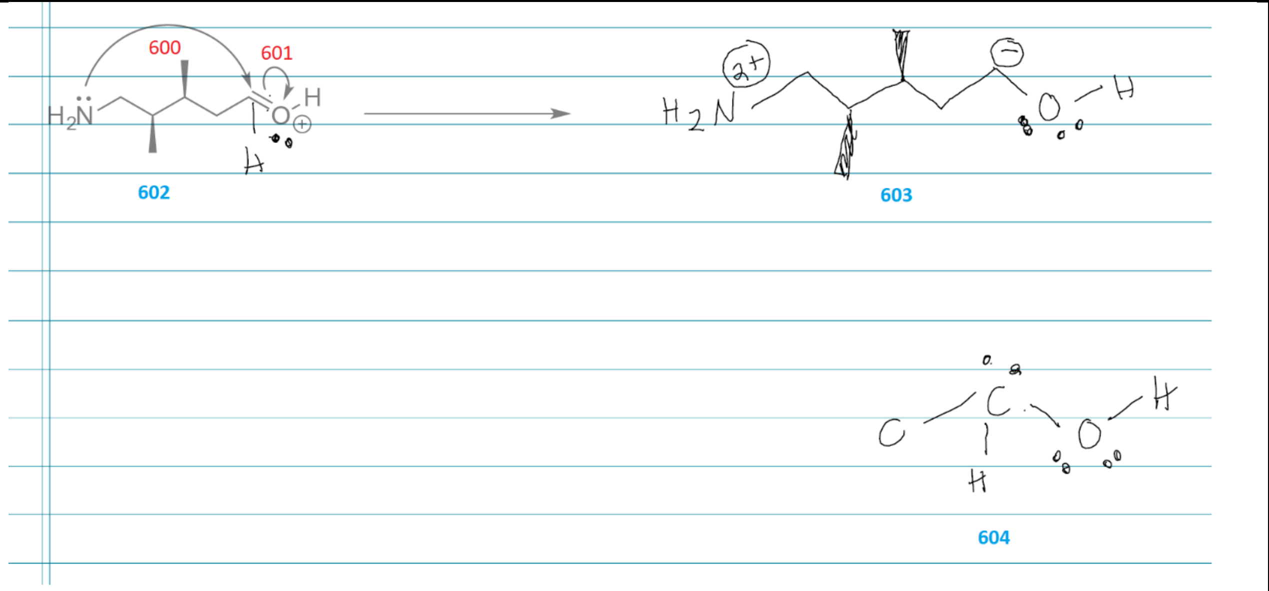


#09:	“***Okay so, I'm gonna start by looking at this big one*** *[Arrow 500] […]* ***That's just what I'm drawn to****, I think. Looks like the first one. And no yeah, the first one, um* ***so we've got a pair of electrons that are going to that atom*** *[green circle on molecule 503], and then an arrow [arrow 501] from from looking at the second arrow now, an arrow from* ***this bond to the chlorine. So I know right off the bat that that chlorine is going to end up looking like this*** *[…]* ***because it's gonna gain electrons*** *[…]*

	From this, this bond *[…]* ***And I'm just drawing what had happened after this first arrow*** *[arrow 500] […] This could be either a double bond [molecule 512], but I don't think it's a double bond or it could be (...drawing) a negative [molecule 513],* ***it has to be a double bond, I'm pretty sure it's a double bond*** *[molecule 512].”*
Int:	*“Okay, tell me why did you draw it connected to the chlorine, I thought you said that came off or something”*
#09:	***“Um well the chlorine is always gonna be there, I don't, yeah the chlorine is always gonna be there so I just kept it with the chlorine*** *[…]* ***Yeah, um I'm just not sure how the electrons are going to go to that carbon*** *[circled in green]* ***molecule because the carbon has, as of right, right from the beginning****, it has two hydrogens and then connections to two other molecules,* ***so that's full, so then gaining another pair of electrons is going to cause problems*** *[…] So,* ***so it gains another pair of electrons and then one of these pairs is gonna go to the chlorine. So that's, that's kinda what's happening****,* ***I'm not sure how to draw the product****, but um, could be a double bond [molecule 512], mmm I'm not sure.”*

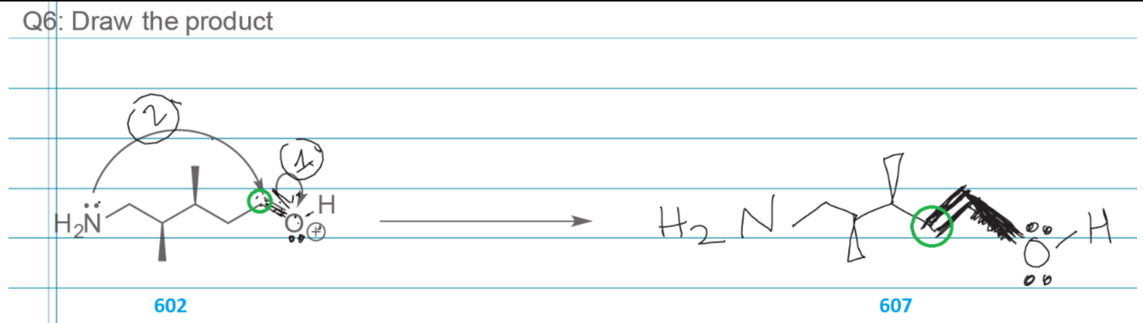
	Question 6
	
#01:	***“So because the arrows*** *[Arrow 600 and 601]* ***again are all pointing to one direction then that’s towards the oxygen****,* ***um something happens to oxygen****.* ***it’s a double bond pointing towards the oxygen*** *[Arrow 601]* ***which means the double bond is going to break, and um that is going to be something charge*** *and then it’s […] and this one goes to there. So then basically* ***the electrons are pointing towards the carbon*** *[Arrow 600] and so.* ***I think this is why we were told to do it step by step because then it’s easier to see the movement of electrons****. The electrons are basically just have to go here. Um. So what happens to this carbon […]* ***because the electron from the double bond move towards the oxygen****,* ***I think this carbon should have a charge*** *[Circled in green on molecule 605] […]* ***I want to just give the electrons to the carbon so that it has a complete octet****.* ***But then I think it will still be charged****. Because right now it’s C- H here, this one has another bond. This carbon and this oxygen and that’s why it has a positive charge.* ***So if I give it the electrons that the arrow*** *[Arrow 600]* ***is pointing from.****”*
Int:	*“Is that what that arrow [Arrow 600] means to you?”*

#01:	*“**That the electrons are going to go to that carbon** [Molecule 608] **yes**. **Because I’m assuming it’s pointed directly at the electrons, I don’t know if I can just cheat and just use this hydrogen instead**. **Cause if I cheat and use this hydrogen then it would be easier to make it like that** [Molecule 607], **And carbon would be happy because it has a bond.”***
Int:	*“I do want to let you know that it is 11:15 and so I don’t want you to be rushed for class, so if you um want to um, give me the best response that you can give that you’ve figure out so far.”*
#01:	*“Uh. I can only end up here, **I don’t know how to figure it out anywhere else**. **So the electrons are going to move from the nitrogen to the carbon** [Arrow 98], **but I don’t know what happens to that**.”*

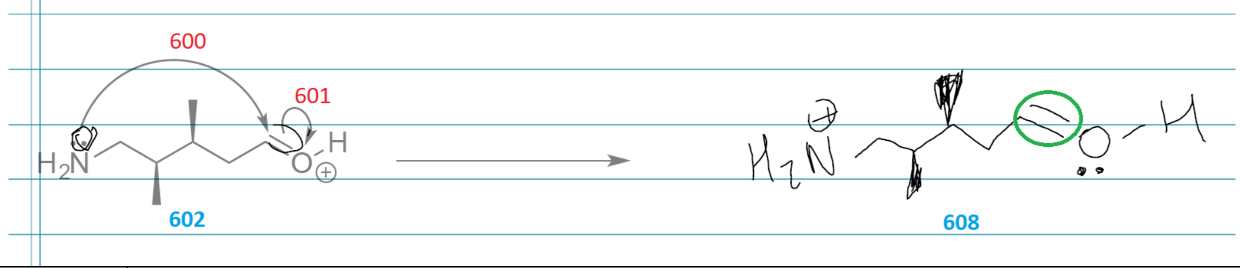


#02:	*“**I see the transfer of electrons** [Arrow 600] **from the nitrogen to the carbon, and the transfer of the electrons** [Arrow 601] **from the double bond to the oxygen**. **I’m just going to draw that** [molecule 603]. Okay since that has a positive charge. Then I know there’s a lone pair here. One two three four five. Six minus 5 would be positive. **So I think the electrons from the double bond** [arrow 601] **go to the oxygen**. **So it would have no more formal charge now**. And then**. I’m not sure how the electron pair would go. On this carbon**. Um. **Let me draw the carbon** [Molecule 604]. And **I know from here there’s only one hydrogen bonding to it** […] **it has no formal charge, and if you count the bonds**. **One two three four**. **So I know there would be hydrogen bonded here. That’s linked to another carbon**. **So I guess there would be lone pairs on the carbon. So then it would have a negative formal charge**. **And then for the nitrogen. I guess it would have two plus the formal charge** [Nitrogen atom on molecule 603] […] **well it has five to begin with, but there’s only three bonds here**. **So five minus three is two**. Uhh yeah.”*
Int:	*“Does those charges work out for you given what you had in the beginning.”*
#02:	*“Yes I think so. **There’s only a positive and I feel like the overall formal charge, this is going to be positive plus two minus one**.”*
Int:	*“Okay, so when you see the arrow, can you just talk to me a little about, more about what’s going through your head. How do you know that means electrons are transferred?”*

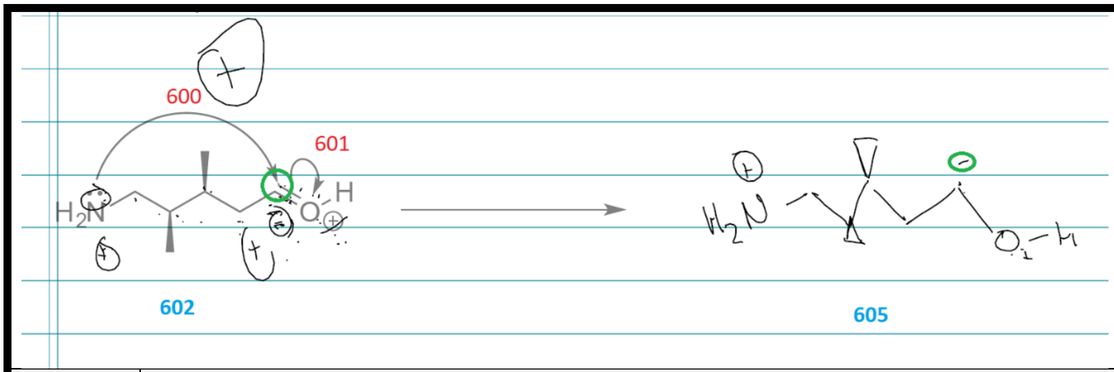
#02: “***Uh the arrow*** *[Arrow 602]* ***goes from. like in this case literally the electrons into another***. ***To another atom***. *And for things that go from a bond,* ***well things are presented in the bonds are the electrons being shared. And when that has an arrow*** *[Arrow 601]* ***from that to another***, ***I assume the electrons are just moving to the other atom***.”



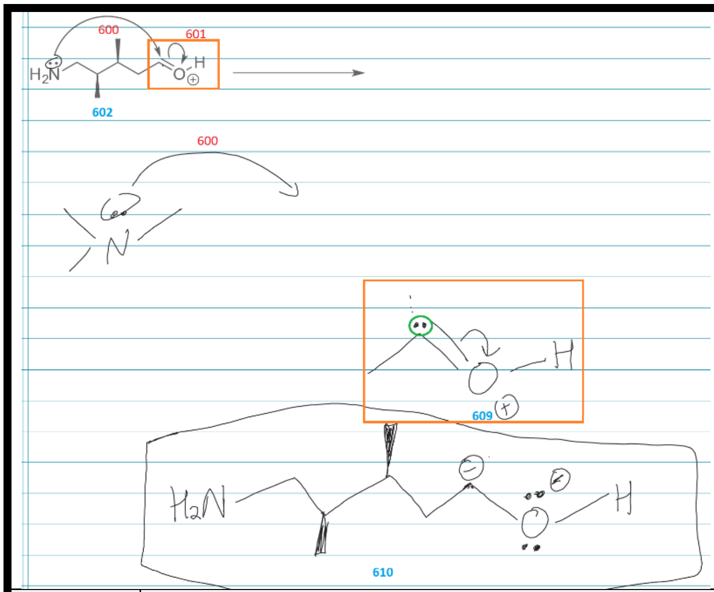
#05: “***Um so the first thing I noticed really is that um these electrons*** *[arrow labelled 2 by the participant]* ***are being transferred to here*** *[carbon atom circled in green on molecule 602] […]* ***And this double bond is gonna be taken away*** *[arrow labelled 1 by the participant],* ***uh yeah it's just gonna be broken to put the electrons on the oxygen*** *and right now oxygen has a positive charge so six and there's like three bonds so there's have to be, kay so right now there's only one pair of electrons […]* ***Um and then, so right and okay so what they want to do is do like this so now um so now the oxygen doesn't have any charge but I'd have to bring my so the electrons*** *[arrow labelled 2 by the participant]* ***are coming over and they'd be here now*** *[circled in green on molecule 602] […] So this has to be a single bond [Carbon-Oxygen bond on molecule 607] and so I guess* ***I would just, yeah I would put the double bond*** *[double bond on molecule 607]. […]* ***Yeah 'cause I could put it here*** *and this one has to have the electrons happen.”*



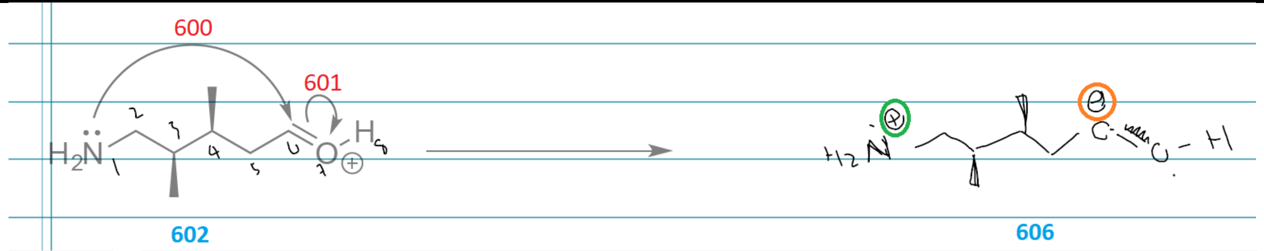
#07: *“I know that* ***electrons will create bonds*** *so they move all the way over to this [inaudible] oxygen. Which has a positive charge, that means it’s missing a pair of electrons so it’s not happy. But I see that-****this double bond or pi bond broke*** *[Arrow 601] […]* ***which means it adds electrons to the oxygen making that octet full*** *making it happy but this double bond is not- I guess* ***this carbon would not be happy ‘cause it’s lost a bond so the pair of electrons from the nitrogen*** *[Arrow 600] come all the way over to fill up -* ***to keep that double bond****- [circled in green on molecule 608] keeping that central carbon atom happy.”*



#08:	*“**So if we’re ever getting rid of this positive charge** [positively charge oxygen on molecule 116], **which is also I’m going to say frowned upon, by like chemists.**”*
Int:	*“What’s frowned upon?”*
	*“**um having a positive charge on an oxygen molecule** […] **like we always want to have oxygen either be neutral or negative**, **so by pulling these electrons out of this bond** [arrow 601], we actually make, um. We just get rid of this and we get a single bond. um so we take this and **the other arrow** [Arrow 600] **is taking this lone pair. I’m not sure if it’s putting on this, I think it’s putting on this atom** [carbon atom circled in green on molecule 602] […] to the atom. **Okay so that would make it. I guess it would have a minus on this atom** [circled in green on molecule 605], **which doesn’t really make sense because again it’s a carbon which is not very electronegative.**”*
Int:	*“Why is there going to be a minus on the atom?”*
#08:	*“**Uh if we’re taking on a lone pair** [arrow 600] **and putting on a. like a lone pair usually has a negative charge**. **And so we would put that on there** [circled in green on molecule 605]. […] we would have like a. single bond there, so it would be like a, like an alcohol I guess is what we’re making. […] We have an amine group here [Nitrogen on molecule 116]. Which is going to become negative. No no no. **it’s going to become positive taking this lone pair off** [arrow 600]. **Which I think is a good thing because we want nitrogen to be positive** [positively charged nitrogen on molecule 605] **more often than it to be negative** […] um from what I know. But now **I don’t think it’s a good idea, like, making a carbon negative** [circled in green on molecule 605]. **If this is actually what is going on here. […] um, but I guess like I don’t make the rules so.**”*



#09: *“Okay,* ***so we've got a pair of electrons from the nitrogen*** *[arrow 601], again here's this excess business going on […] Because there are two hydrogens coming off of that nitrogen […] So there, already that has three bonds,* ***so this pair of electrons I'm assuming is, it wants to go away so that's why it's leaving via the curved arrows*** *[arrow 601], you can see, so* ***then it's going to that carbon*** *[circled in green on molecule 609] […]* ***But there's already double bonds from there […] That means that the double bond needs to move*** *[…]* ***this arrow*** *[Arrow 601]* ***that comes to the oxygen*** *[…]* ***That's going to break the double bond and the oxygen is gonna have an extra one, two, three, four****, and extra pair of lone pair, or not lone pairs,* ***electrons, so that's gonna look like that*** *[Oxygen atom on molecule 610] […]* ***And then you draw a negative charge there****,* ***I think that positive charge just disappears*** *[…]* ***When these electrons leave****,* ***that's gonna be the way it is, I'm happy there****,* ***and I know that this is most likely what's gonna happen with that double bond, with the negative charge, those pair of electrons****.”*

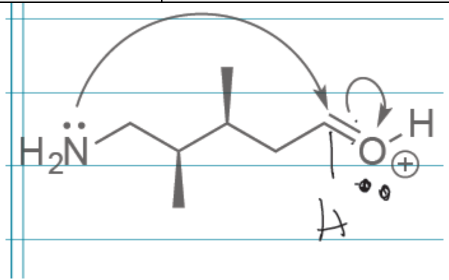


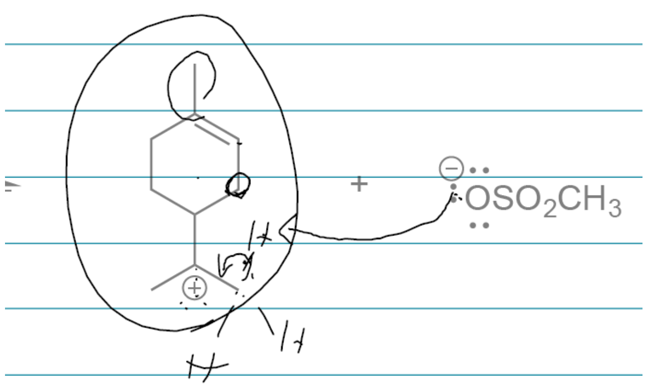
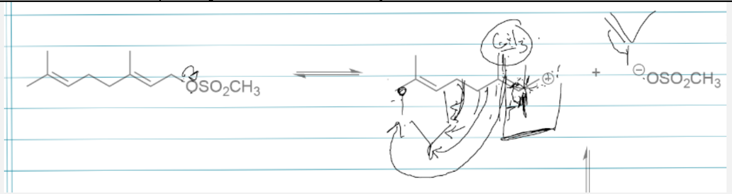
#11: ***“The one from the double bond*** *[Arrow 601]* ***going to the oxygen I would assume this is the double bond breaking and then it forms the extra - gives it the extra electron to the oxygen****.* ***Since it has a positive charge I think it kinda removes it****. […] Positive charge. […] Hmm, you have* ***I don’t if it’s one or two electron but those electron from the nitrogen*** *[Arrow 600]* ***moves to the carbon where I labeled six*** *[molecule 602]. […] I drew a positive on the nitrogen [molecule 606] and a negative on the carbon [molecule 606] […] Well it gave,* ***the nitrogen gave an electron away*** *[Arrow 600]* ***but I think it was one*** *[result is the black dot, an electron, above the nitrogen atom on molecule 606]. And that just results in less negative so the positive goes there [circled in green on molecule 606],* ***carbon took one and that just adds up****, [inaudible]* ***um adds in extra electron and become more negative*** *[circled in orange on molecule 606].”*

Int:	*“Okay. So did it kind of split that lone pair between the two atoms?”*
#11:	*“**Hmm, that’s kind of what I’m showing**... don't’ know if that’s right though.”*
Int:	*“But that’s what you think?”*
#11:	*“**Yeah**. […] **It’s probably what I would have drawn**.”*

Appendix 24: All responses regarding charge definitions

Negative Charges	
#01:	*"because it has a minus charge it has it technically has one extra electron that it doesn't normally have."*
#02:	*"I just count across, so like one two three four five. Five minus the number of electrons and pairs of electrons. Five minus six makes it negative one formal charge."*
#03:	*"It's going to gain a positive charge so it's going to lose an electron pair towards there."*
#04:	*"We learned in class at least that negative charges mean that it must've uh gained, or has more lone pairs."*
#05:	*"In order for these to b- break uh um it, so if this is positive then it's missing electrons and if this is negative, has too many."*
#06:	*"The oxygen is n- how now has a negative charge, how? Oh okay 'cause the bond came here, so this now, this oxygen now has uh those six valence pairs, or the six valence electrons [...] Uh that makes it a negative charge because it can- it wants six and it has seven because of that right there."*
#07:	*"If it's a negative charge it's gained a pair of electrons."*
#08:	*"Oh, well because we have a minus [..] which means we have too many electrons and then there's no minus there's a double bond [inaudible] over there."*
#09:	*"I believe, um and that gained the electrons so that's negative"*
#11:	*"the whole oxygen thingy is gaining an extra electron to have the negative."*
#12:	*"Okay. Um so, well right away I see there is a negative charge on the oxygen, um so that means it has too many electrons that I guess belong to it."*
#13:	*"So um and it's gonna have negative charge because it has no charge here so, and it's being given electrons so it's gonna have a negative charge."*

Positive Charges	
#01:	*"Because there's a plus and that means it is missing um one, it's missing usual one, um. It only has six electrons um and it would've had it had seven and it had to lose one to become more stable."*
	
#02:	*"Since that has a positive charge. Then I know there's a lone pair here. One two three four five. Six minus 5 would be positive. So I think the electrons from the double bond go to the oxygen."*

	
#03:	*“Okay, yeah so I can see from these two. I’ve got that positive charge on the carbon. So that positive charge tells me that. It has a lone pair of electrons. Oh no, wait a minute. it doesn’t have a lone pair or electrons, it just have three bonds, so it wants to form another bond, um so it has a positive charge it wants to bring in electrons. So it’s going to take it’s.”*
#04:	*“Because, because this is a positive charge, it doesn't have the electrons… [..] Which created this cyclohexane ring, and then this one is left with a positive formal charge because it lost that bond, or the, the electrons from it.”*
#05:	*“So if this is positive then it's missing electrons and if this is negative, has too many.”*
#06:	*“Okay so now and uh okay so more arrows here uh this char- this bond here looks to be going to this oxygen because the oxygen is positive, um so it's getting another uh, it's because of its positive charge it takes this bond here and that's this H2O right here that's where that came from [00:03:44.04] Lucas: Oh well it wants, it wants to have uh, 'cause it has the valence electrons but oxygen like having six electrons around it right now it only has one, two, three, four, five .. […] Uh so it wants, it wants to take this electron basically.”*
#07:	*“If you’ve lost a pair of electrons it becomes a plus charge--positive charge.”*
	
#08:	*“But this negative shows at the electrons of this bond moves to this “O” so moving these electrons and breaking these bond and moving the electrons to the “O” gives the carbon here a positive charge.”*
#09:	*“If it's positive that there's maybe a lack of electrons.”*
#11:	*“Since you lose an electron that would cause a positive charge here.”*
#12:	*“There's a positive charge on this carbon, which means it's missing an electron.”*
#13:	*“This carbon though is now lacking a bond so it's gonna have, and there's no lone pair for it to take from this bond because it shows that the electrons are going this way so it's gonna have a positive.”*

Appendix 25: All responses describing charges as important

Int:	*“That’s okay. Um. Rather than trying to remember the equation. Um . how about “when you’re looking at a reaction like this. Is charge important to tell you what’s going on?”*
#03:	*“Oh yeah because the charge uh to move molecules around you have to attach things, you go from having these two separate now they’re together, but to attach things together you have to use the charges and the lone pair of electrons to be able to give and receive electrons and make and form bonds. So when that has a positive charge, it wants to grab electrons to make it’s charge neutral. And something that has a negative charge wants to give it’s electrons so it can become neutral as well. Cause all atoms are happy when they are neutral.”*
#05:	*“Um I guess they're pretty important because like it shows like I guess if it's like missing, so if it's positive […] Then I guess it would be missing either like a bond or like a pair of electrons or something or like kind of like the H and the um O here, they get like bonded together kind of thing, so I guess it kind of shows you that something's happening there.”*
#06:	*“Um, again charge was everything, which I think is why I wasn't getting the uh, the uh cyclohexane one because I think I might've had to think of it outside of charge and I'm pretty bad at that.”*
Int:	*“So how um, how did, or was a charge was important to you as you were solving this problem?”*
#07:	*“Yeah […] Um, this third step here it had to, um, there were no charges anywhere, the charge was indicating that something wasn’t full, it’s octet wasn't full. And then the final step it showed that- you need- the double bond was I guess formed and then you needed to chan-, there was no more charges anywhere so it indicated that the charges somehow had to move somewhere and then fill up an octet or change into like a bond of some sort and then just disappear. Or change into a double bond and then it has to react with something. And then yeah.”*
#08:	*“Um, well the charge is like pretty important I guess, cause like the whole idea of what's going on, and like breaking bonds and making bonds is the electrons and so the electrons like influence the charge.”*
#09:	*“The charge is important if I know what's going on […] Because it gives me, like it's kind of something, the first thing that I look at, like boom there's a charge there it's like a hey like a little red flag”*
Int:	*“Okay, so when you look at a reaction like this um, how important is charge to you to help understand what’s going on [pause] is charge important.”*
#11:	*“Yeah, so I would say pretty Important [laughs].”*
#12:	*“I think it's quite important just because, um I think I mentioned earlier that like the charges need to be balanced, um so when I'm doing my reaction through equations um I always check the charges to make sure because um I know I've made a mistake if I have like two um positive charges on one side and then a positive and a negative on the other because then something doesn't add up and I have to recheck everything and find my mistake because it should be balanced.”*
#13:	*“Uh it's very important, um it kinda helps keep track of where your electrons are and where, what has too many or too little bonds, not too many but like for the octet rule [..] Um it kinda helps predict what's gonna happen because if you see a charge you kinda know something's gonna happen to it.”*