CONTENT-RELATED INTERACTIONS AND METHODS OF REASONING
WITHIN SELF-INITIATED ORGANIC CHEMISTRY STUDY GROUPS

by

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TABLE OF CONTENTS

LIST OF TABLES ................................................................. 8
LIST OF FIGURES ................................................................. 10
ABSTRACT ........................................................................... 13
CHAPTER 1: INTRODUCTION ................................................... 15
CHAPTER 2: CONTENT-RELATED INTERACTIONS IN SELF-
INITIATED STUDY GROUPS ................................................... 20
  Framework ......................................................................... 20
  Methodology ....................................................................... 24
    Goals and Research Questions ........................................... 24
    Setting ............................................................................. 25
    Participants ...................................................................... 26
    Recruitment of Students ................................................... 27
  Data Collection .................................................................... 27
  Analysis of Data .................................................................. 32
  Limitations to Research Methodology .................................. 33
Results ................................................................................... 35
  Social Regulation ............................................................... 36
    Teaching Interaction ......................................................... 39
    Tutoring Interaction ........................................................ 41
    Co-constructing Interaction ............................................. 44
  Content Processing ............................................................. 46
  Influential Factors ............................................................. 49
    Group Composition Features ............................................ 50
    Task Features ................................................................... 53
Discussion, Conclusions, and Implications ................................. 62
CHAPTER 3: STUDENT REASONING ABOUT ORGANIC
CHEMISTRY CONCEPTS ........................................................ 68
TABLE OF CONTENTS

Framework .................................................................................................................. 68
Methodology ............................................................................................................. 75
  *Goals and Research Questions* ........................................................................... 75
  *Data Analysis* ...................................................................................................... 76
Results ....................................................................................................................... 78
  *Reasoning Processes* ......................................................................................... 78
  *Influential Factors* .............................................................................................. 81
    *Content Focus* .................................................................................................. 81
    *Social Regulation* ............................................................................................ 93
  *Student Content Processing and Methods of Reasoning* .................................. 97
Discussion, Conclusions, and Implications ............................................................. 100

CHAPTER 4: CONCLUSIONS, IMPLICATIONS, AND FUTURE WORK
.................................................................................................................................... 108
  Summary of Results ............................................................................................... 108
  Conclusions ............................................................................................................ 109
  Implications ........................................................................................................... 112
  Future Work .......................................................................................................... 115

APPENDIX A: CHEMICAL REASONING IN FIRST SEMESTER ORGANIC CHEMISTRY
.................................................................................................................................... 117
  Model-Based Reasoning ....................................................................................... 117
  Case-Based Reasoning .......................................................................................... 122
  Rule-Based Reasoning ........................................................................................... 125
  Examples of Student Reasoning ........................................................................... 127

APPENDIX B: FURTHER DESCRIPTION OF CODING SCHEME .....133
  Student Interactions .............................................................................................. 133
  Levels of Content Processing .............................................................................. 138
# TABLE OF CONTENTS-Continued

Student Reasoning........................................................................................................... 142  
Type of Subject .................................................................................................................. 147  
Prompt .................................................................................................................................. 150  

**APPENDIX C: EXAMPLES OF PROBLEMS THAT REQUIRE DIFFERENT TYPES OF SKILLS** ................................................................................................................................. 153  
Problems that Require Different Types of Reasoning .................................................. 153  
  *Rule-Based Reasoning* ........................................................................................................ 153  
  *Case-Based Reasoning* ..................................................................................................... 154  
  *Model-Based Reasoning* .................................................................................................. 155  
Problems that Elicit Different Levels of Content Processing .................................... 156  
  *Remember* ..................................................................................................................... 156  
  *Understand* ..................................................................................................................... 157  
  *Apply* ................................................................................................................................ 157  
  *Analyze* ............................................................................................................................ 158  
  *Create* .............................................................................................................................. 159  

**APPENDIX D: ADDITIONAL FIGURES** .................................................................. 161  

**APPENDIX E: INSTITUTIONAL REVIEW BOARD APPROVAL MATERIALS** ......... 166  
  Human Subject Approval Letter ....................................................................................... 166  
  Continuing Review Form .................................................................................................. 167  
  Informed Consent ............................................................................................................. 168  

**APPENDIX F: EXAMPLE STUDY GROUP TRANSCRIPT** .................................... 170  

REFERENCES ..................................................................................................................... 209
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Percentage of study sessions observed for each exam in the first semester of Organic Chemistry</td>
<td>31</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Percentage of content-related words associated with three types of interactions for the different groups and study sessions observed as part of this study</td>
<td>37</td>
</tr>
<tr>
<td>Table 2.3</td>
<td>Average percentages of on-topic words associated with different levels of content processing corresponding to different types of interactions in all of the study groups</td>
<td>48</td>
</tr>
<tr>
<td>Table 2.4</td>
<td>Levels of content processing in study groups as demonstrated across each unit exam</td>
<td>54</td>
</tr>
<tr>
<td>Table 2.5</td>
<td>Discussion prompts and the levels of content processing that correspond to each type of prompt</td>
<td>57</td>
</tr>
<tr>
<td>Table 2.6</td>
<td>Levels of content processing which students engaged in for each of four different types of problems proposed by instructors or created by students</td>
<td>58</td>
</tr>
<tr>
<td>Table 2.7</td>
<td>Types of interactions as related to different sources of discussion</td>
<td>61</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Percentage of words corresponding to each method of reasoning, and relative to each study session that was observed, where SBR is symbol-based reasoning, RBR is rule-based reasoning, CBR is case-based reasoning, and MBR is model-based reasoning</td>
<td>80</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Ways in which study groups discussed organic chemistry with respect to five different content focuses</td>
<td>83</td>
</tr>
<tr>
<td>Table 3.3</td>
<td>Types of reasoning that students used in preparation for each exam, reported as a percentage of the words that students spoke in each given study session</td>
<td>91</td>
</tr>
<tr>
<td>Table 3.4</td>
<td>Eight of the most common types of instructor-provided problems from which students worked, and the type of reasoning which corresponded to each problem</td>
<td>93</td>
</tr>
<tr>
<td>Table 3.5</td>
<td>Types of interactions representative of each method of reasoning</td>
<td>94</td>
</tr>
</tbody>
</table>
LIST OF TABLES-Continued

Table 3.6. Types of reasoning that students used, corresponding to different cognitive levels of content processing ...............................................................99

Table B.1. Further Examples of Student Reasoning........................................146
LIST OF FIGURES

Figure 2.1. Structure of organic compound that was the focus of students’ self-created nomenclature problem .................................................................40

Figure 2.2. An instructor-provided problem requiring students to propose the reactant and intermediate of a halogenation problem ...........................................41

Figure 2.3. A student’s notes regarding an oxidation reaction which included an inconsistency in the intermediate and final product .................................42

Figure 2.4. A reaction for which students were required to propose a possible synthetic pathway ......................................................................................45

Figure 2.5. A student-created problem which required the respondent to predict the product under given reaction conditions ..............................................60

Figure 3.1. An instructor-provided nomenclature problem ........................................84

Figure 3.2. A student-created problem which required the study group to find the product of a reaction ...........................................................................85

Figure 3.3. An instructor-provided problem which required the students to propose a synthetic pathway .................................................................86

Figure 3.4. An instructor-provided problem requiring students to propose a mechanism to account for several different products.................................89

Figure 3.5. A student-created prompt that elicited a conversation regarding the reactivity of substrates in S_N1 reactions .................................................95

Figure A.1. Sigma and pi bonding ................................................................118

Figure A.2. Example of several structures which share the common alcohol functional group ..............................................................................................123

Figure A.3. Example of NMR splitting that would be characteristic of an ethyl fragment. In this case, the example corresponds to CH_3CH_2Cl ..............124

Figure A.4. A prompt which requires students to determine which compound is most acidic .........................................................................................127
LIST OF FIGURES-Continued

Figure A.5. A prompt requiring students to translate a representation.........129

Figure A.6. The order of structures drawn by a student using rule-based reasoning in order to come to a solution for a chair conformation problem...........129

Figure A.7. A problem requiring students to draw a mechanism and predict the product of a reaction.........................................................130

Figure A.8. The correct mechanism and final product corresponding to a required mechanism task.................................................................131

Figure D.1. Average percentages of on-topic words associated with different levels of content processing corresponding to different types of interactions in all of the study groups (as seen in Table 2.3) .........................158

Figure D.2. Levels of content processing in study groups as demonstrated across each unit exam (as seen in Table 2.4) .........................158

Figure D.3. Discussion prompts and the levels of content processing that corresponded to each type of prompt (as seen in Table 2.5) .................159

Figure D.4. Levels of content processing for each of four different types of problems either a) proposed by instructors or b) created by students (as seen in Table 2.6) .................................................................160

Figure D.5. Types of interactions which were generated as a result of different sources of discussion (as seen in Table 2.7) .........................160

Figure D.6. Ways in which study groups discussed organic chemistry with respect to five different content focuses (as seen in Table 3.2) .................161

Figure D.7. Types of reasoning that students used in preparation for each exam, reported as a percentage of the words that students spoke in each given study session (as seen in Table 3.3) .........................161

Figure D.8. Types of interactions representative of each method of reasoning (as seen in Table 3.5) .................................................................162
Figure D.9. Types of reasoning that students used, corresponding to different cognitive levels of content processing (as seen in Table 3.6) ..................162
ABSTRACT

Students often use study groups to prepare for class or exams; yet to date, we know very little about how these groups actually function. This study looked at the ways in which undergraduate organic chemistry students prepared for exams through self-initiated study groups. We sought to characterize the methods of social regulation, levels of content processing, and types of reasoning processes used by students within their groups. Our first-hand observations of students gave us a means to qualitatively understand how undergraduate chemistry students interacted and collaborated, and how this affected the ways in which they engaged with chemistry concepts and ideas. Our analysis showed that groups engaged in predominantly three types of interactions when discussing chemistry content: co-construction, teaching, and tutoring. Although each group engaged in each of these types of interactions at some point, their prevalence varied between groups and group members. Our analysis suggests that the types of interactions that were most common depended on the relative content knowledge of the group members as well as on the difficulty of the tasks in which they were engaged.

Additionally, we were interested in characterizing the reasoning methods used by students within their study groups. In particular, we were interested in understanding how students worked from given premises within a problem to come to some solution. We found that students used a combination of three content-relevant methods of reasoning: model-based reasoning, case-based reasoning, or rule-based reasoning, in conjunction with one chemically-irrelevant method of reasoning: symbol-based reasoning. The most common way for groups to reason was to use rules as the basis of
their justification, whereas the least common way was for students to work from a model. In general, student reasoning correlated strongly to the subject matter to which students were paying attention, and was only weakly related to student interactions.

Overall, results from this study may help instructors to construct appropriate tasks to guide what and how students study outside of the classroom. We found that students had a decidedly strategic approach in their study groups, relying heavily on material provided by their instructors, and using the reasoning strategies that resulted in the lowest levels of content processing. Because students relied extensively on instructor-provided tasks, we see the instructor as having a unique influence on the groups that were formed. We suggest that instructors create more opportunities for students to explore model-based reasoning, and to create opportunities for students to be able to co-construct in a collaborative manner within the context of their organic chemistry course.
CHAPTER 1: INTRODUCTION

Collaborative learning within small groups has been shown to be valuable in increasing cognitive and affective gains for students (Prince, 2004). Specifically, students who collaborate show increased potential for critical thinking as they discuss multiple and sometimes competing ideas (Gokhale, 1995). The social environment of the group is crucial, and the presence of social ties among group members has been linked to a positive learning environment and retention within academic programs (Del Carlo & Bodner, 2009; Kreijns, Kirschner, & Jochems, 2003; Rau & Heyl, 1990). Yet the specific nature of social interactions among group members may be variable, as not every group participates in the same manner (Draskovic, Holdrinet, Butte, Bolhuis, & Van Leeuwe, 2004; Miller, Trimbur, & Wilkes, 1994). In fact, collaborative groups may face several challenges, as some groups have difficulties learning from or resolving conflict (Oliveira & Sadler, 2008), or other groups have non-equitable levels of student participation (Bianchini, 1997). A successful collaborative learning environment depends on several factors, and group interactions are one aspect that may help one to determine the mechanism for learning within a group (Hausmann, Chi, & Roy, 2004). As students interact in different ways, the quality and depth of their discussion is affected (Webb, 1992). Thus, the collaborative nature of group work is shown to be inherently variable, affecting both the cognitive and affective gains expected for students.

Much of the research that has been conducted on the subject of collaborative group work has come from observations of students involved in teacher-assigned tasks in diverse classroom settings. Much less is known about the structure and dynamics of self-
initiated student groups formed outside of the classroom for studying purposes. A better understanding of these study groups would help us to understand how productive collaborative engagement emerges in different contexts, and would allow us to identify potential strategies to support student thinking in these environments. There have been a few research studies which have examined the benefits of students working in study groups. Such research has found that students studying in self-formed groups are expected to increase their level of studying to a deeper approach, compared to students who study alone (Tang, 1993). This is possible because the process of working together encourages interactions such as analyzing, relating, discussing, and debating, which are higher cognitive strategies. Additionally, it has been found that students who study in groups score higher on exams, particularly for those that require a deeper understanding of the content (Sokolove, & Marbach-Ad, 1999; Bradshaw & Hendry, 2006). Participating in collaborative study groups appears to be one method of studying which results in positive gains.

Yet the primary data used for analysis of student study habits has originated from student self-reports. Very little information about how students study exists apart from what students have reported to researchers. Common methods of data collection include surveys, questionnaires, and interviews, as it is much harder to observe firsthand how and what a student is studying. In fact, in the rare case that students’ study tactics were actually recorded through a computer program, it was found that students did not always self-report accurately, as they tended to report using more study tactics than were actually used (Winne, & Jamieson-Noel, 2002). Because students may not always be aware of
reasoning strategies or group interactions that they are using, nor are they always able to self-report accurately, it is important to be able to observe first-hand what students do while they are studying in groups. Several studies suggest that potential benefits of groups may come as a result of collaborative discussion and explanation of concepts (Hendry, Hyde, & Davy, 2005), although little else is known about how study groups operate, and surprisingly little is known about the potential mechanism of success. The study group represents a complex environment in which social and cognitive factors affect the behaviors of students within the group. In order to better understand the context for learning within a study group, additional qualitative research is needed.

This study will investigate studying practices in the context of self-initiated study groups in organic chemistry. We will focus on the interplay between social, cognitive, and reasoning processes exhibited by the students in these study groups. In particular, the following research questions will be addressed:

— What types of social regulation processes are characteristic of self-initiated study groups in organic chemistry?

— What levels of content processing are commonly present in these types of groups?

— What major types of reasoning approaches do students apply while reviewing organic chemistry content?

— How does the nature of the questions and problems discussed in the study groups, as well as the types of interactions among group members, affect reasoning approaches?
— What levels of content processing are most frequently associated with the
different types of reasoning observed in the study groups?

In order to answer these research questions, we designed a qualitative research
study that used direct observation of student study groups as they prepared for their first
semester organic chemistry course. Data from our research were analyzed in two
separate studies. The first study investigated students’ interactions in conjunction with
their levels of content processing. The second study investigated the methods of
reasoning that students used to discuss organic chemistry content.

Because collaborative work in independent study groups can be expected to be
self-selected and self-regulated by the participating students, direct observation and
analysis of these types of groups could help us identify potential strategies to support
student thinking outside the classroom. Having a more thorough understanding of the
nature of student study groups will hopefully aid us in our ability to provide support for
future chemistry students as they prepare for and study for their college-level organic
chemistry course. Findings from our research are expected to have implications in the
field of chemistry education research and for college chemistry instructors.

This dissertation has been organized in the following way: chapters two and three
will further explain the theoretical framework, methodology, results, and conclusions
specific to each of the two studies. Although both chapters used the same data source,
these chapters have been organized such that the reader should be able to read them
independently of one other. For this reason, some repetition may be observed between
the two chapters (e.g., the description of some coding results). Chapter four will address
overall conclusions, implications, and future research. Appendix A will give further insight into how students in their first semester of organic chemistry might be expected to reason about chemistry topics, and Appendix B will describe how decisions were made pertaining to the application of codes. Additional appendices give examples of problems that could elicit different types of skills (Appendix C), provide supplementary figures (Appendix D), show human subjects’ approval (Appendix E), and provide an example of a representative study group transcript (Appendix F).
CHAPTER 2: CONTENT-RELATED INTERACTIONS IN SELF-INITIATED STUDY GROUPS

Framework

Recent research in the area of collaborative learning has shifted from a focus on the function of individuals within the group to a more broad perspective of the group as a core unit of analysis. This shift in focus has allowed the researcher to better understand the role that certain variables play in mediating group interactions and reasoning ability (Dillenbourg, Baker, Blaye, & O’Malley, 1996). Because the nature of collaborative group behavior is inherently variable, there is a need to better understand the environments which lead to higher levels of engagement among students, as well as the conditions under which all students may be involved in productive reasoning. Research indicates that there are many challenges associated with encouraging collaborative groups to engage in effective reasoning behavior (Webb, Ender, & Lewis, 1986). This points to the need for a better characterization of the types of interactions that contribute to or inhibit productive reasoning and co-construction of understanding in collaborative groups.

Collaborative group work may be valuable for students working within the classroom or with independent student study groups. In fact, several group processes may be responsible for success within the group, as students engage in quality argumentation with their group members (Chin, O’Donnell, & Jinks, 2000; Gokhale, 1995) and learn from their peers’ problem-solving approaches (Azmitia, 1988). Students
commonly use collaborative group efforts to explain concepts to one another, which may lead to higher learning gains (Cooper, Cox, Nammouz, & Case, 2008). All in all, the collaborative group is most successful when its participants are intellectually active and work together to construct their own understanding (Smith & MacGregor, 1992). When students are jointly engaged and have a high degree of mutuality, they are more likely to be engaged in a deeper level of discussion and to see greater success for its members.

Understanding the conditions that lead to successful collaborative discussion is of great importance within science education. Quality discussion among group members is associated with higher learning outcomes and a greater ability to construct scientific arguments (Richmond & Striley, 1996; Webb, 1992). For this reason, many educators may be interested in how their students discuss science content within collaborative groups. In many cases, the effectiveness of group discussion is dependent on student interactions within the group, and groups with more effective collaboration methods are more likely to show reciprocal discussion of content as they jointly construct knowledge (Chi, Roy, & Hausmann, 2008; Oliveira & Sadler, 2008; Woolley, Chabris, Pentland, Hashimi, & Malone, 2010). The nature of student interactions within collaborative groups is, however, inherently variable (Barron, 2000, 2003; Oliveira & Sadler, 2008; Volet, Summers, & Thurman, 2009a). Not all groups demonstrate high levels of mutuality, nor do all groups communicate effectively (Barron, 2000, 2003; Okebukola & Ogunniyi, 2006). To this end, it has been suggested that the types of social regulation and levels of content processing that are reflective of groups may be indicative of productive engagement and participation among students (Volet et al., 2009a).
Social regulation may be described as the process through which students socially regulate each other’s learning. On the one hand, individual students within a group might exert influence on others as they become more confident in their understanding of a particular subject and share that information with others in the group. On the other hand, multiple students may reciprocally co-regulate the cognitive and metacognitive processes of group members (Volet et al., 2009a). The act of regulation is dynamic and changes direction as different parties contribute to the social regulation of the group. At the same time that students mutually regulate the learning of those in the group, individuals additionally self-regulate their own understanding of concepts. Thus, the regulatory mechanisms seen within collaborative group work are inherently interdependent and fluctuate between the different modes (Vauras, Iiskala, Kajamies, Kinnunen, & Lehtinen, 2003; Volet, Vauras, & Salonen, 2009b).

When considering methods of social regulation, it is expected that students will benefit the most from co-regulation when working within groups (McCaslin, 2009; Volet et al., 2009a). As students co-regulate their learning, they demonstrate their ability to collaboratively monitor and co-construct a shared understanding of a given subject. Additionally, students who co-regulate are active participants within a group, indicating their capacity to contribute to and engage in group learning activities.

Groups which engage in effective social regulation are likely to be more productive than those that do not. This is a necessary though not sufficient condition for determining productive group work. The other dimension that might be considered when assessing the effectiveness of a group is the level of content processing demonstrated by
its constituents. By content processing, we refer to the mental activities used by students to process content knowledge (Volet, et al., 2009a). It is the hope that groups would use their resources to engage in quality discussion at high levels of content processing by building explanations, developing models, drawing inferences, synthesizing ideas, or critically evaluating arguments.

It is a common assertion among researchers that sustained, high-level content processing is desirable among students in collaborative groups (Jackson & Prosser, 1985; King, 2002; Prince, 2004). The process of working at high levels likely helps students to enhance their critical thinking and problem-solving abilities, which are generally not addressed when students work from low-levels of content processing (such as memorizing definitions or reviewing facts).

Certain types of interactions may enhance or detract from group levels of content processing (Cohen, 1994). For example, a question-answering interaction has the potential to enhance peer discussion by focusing the dialogue on issues pertaining to problem-solving (King, 1991); however, it has been demonstrated that the depth of a conversation depends greatly on the types of questions that are asked (Chin & Brown, 2000; de Jesus, Almeida, Teixeira-Dias, & Watts, 2006). Students often pose simple recall questions that lead to shallow discussion, and in many cases, students spend the greatest percentage of their time at the most concrete levels of problem-solving (Cohen, 1994). Thus, although certain interactions are correlated to success of groups, these interactions must also be coupled with in-depth discussion of the science content.
From this perspective, analyzing the factors that could affect the nature of both social regulation and content processing during collaborative work is critical in understanding how to promote productive learning interactions. Particularly within the context of student study groups, where conflicting studies have shown variable outcomes as a result of group work (Bradshaw & Hendry, 2006), it would be helpful to understand the factors related to these two dimensions. As students prepare together in study groups, several group and contextual features likely impact the depth of student engagement and the interactions which they use to communicate. It is beneficial for educational researchers as well as practitioners to investigate these features in order to understand how the collaborative group interacts in the most productive manner.

Methodology

**Goals and Research Questions**

The central goal of this study was to investigate the nature of the collaborative interactions in study groups independently organized by science and engineering majors enrolled in organic chemistry courses. In particular, our investigation was guided by the following research questions:

— What types of social regulation processes are characteristic of self-initiated study groups?

— What levels of content processing are commonly present in these types of groups?

— What factors influence the nature of these social and cognitive processes?
Setting

This study took place at the University of Arizona. This is a university that has an emphasis on research and an enrollment of approximately thirty thousand undergraduate students (“The UA Factbook”). The Chemistry and Biochemistry Department offers classes to students every year, with approximately 1000 students enrolled in organic chemistry each semester. Organic chemistry courses are generally taught by lecturers in the department (either full-time or adjunct). Faculty members also teach organic chemistry, although often only the first semester of the course. The class size for the lecture portion of this class ranges from around 60 (for the honors’ and majors’ classes) to about 250 for the general sections. The lab portion of the course is taught by graduate student teaching assistants in the department, and classroom size is limited to 24 students or less per lab. In addition to the lecture and lab portions of the course, a one-hour optional discussion section is scheduled every week. These discussion sections are led by the instructors.

The Chemistry and Biochemistry Department does not follow a set curriculum in its organic chemistry classes, although all classes use the same textbook (McMurry, 2007). The order of topics, method of presentation, and number of exams is up to the discretion of the instructor. For the students observed in this study, the progression of topics in first semester organic chemistry seemed to follow a similar pattern, regardless of who the instructor was. Students were given four exams in a semester with a comprehensive final exam at the end of the course. Although most instructors seemed to follow the same progression, there was some variability between instructors and course
sections. Content that was covered during the first semester included such topics as nomenclature, stereochemistry, spectroscopy, reactions, and synthesis (see Table 2.1).

Participants

Participants in this study were composed of undergraduate students at the University of Arizona who were enrolled in first semester organic chemistry lecture. These students formed study groups of two or more students in preparation for their organic chemistry course. Some of these groups met regularly throughout the semester, and others ended up meeting only once or twice. Most study groups were formed by students who knew each other well from class or elsewhere, although there were a few groups that were formed through open invitation to the rest of the class.

In addition to these participants, groups sometimes included members who were taking second semester organic chemistry, or students who came to study alongside the group but were not enrolled in a chemistry course. In a few circumstances, teaching assistants (TAs), or even instructors were invited, and made an appearance at the study session.

A total of 131 individuals (69 females and 62 males) were observed in their study groups. Each student was given a code in order to be able to reference the students anonymously. In addition, each study group was given a code. For example, “sg1dec4” refers to study group one, and the date at which this group was observed.
Recruitment of Students

Students were recruited for this project during the Fall semester of 2008 as well as the Spring and Fall semesters of 2009. Originally, students were recruited from their discussion sections to participate in the project. Follow-up communication between interested parties occurred over email or phone. We soon found that students were hesitant to volunteer in this setting. In fact, the only students who participated this first semester were ones that knew the author from lab session as their teaching assistant. In subsequent semesters, participants were recruited by going to lab sections and inviting students to participate. These were smaller groups of students (24 or less) and they had more of an opportunity to ask questions if they were interested in participating. As a result, participation rates increased for both the second and third semesters in which the project was conducted. Students who had indicated an interest in the project were contacted later via email, and subsequent communication continued via email or phone.

Data Collection

General observations were made of each study session to note the meeting location, resources used (such as text book or class notes), and other descriptive details of the group. It was common for students to draw organic structures on a whiteboard for the benefit of the group or in their notes for their own personal use. As much as possible, these figures were recorded so that evidence could be kept of what the students were discussing. All study sessions were audio recorded and later transcribed, and the organic structures were imbedded into the transcriptions in order to provide context for the students’ conversations.
When students were ready to meet with their study groups, a representative would contact the researcher by email to let her know the time and location that the group was meeting. These group meetings took place in a variety of locations, often in the library, in study rooms, or in students’ dormitory lounges. The researcher would arrive to make observations of the groups, and would generally stay for an average length of about 60 minutes per study session. Some observations began with groups as they were just starting their study session. In these cases, it could sometimes be observed how groups began their studying and made decisions about how to start covering content. More often than not, however, the researcher arrived mid-study session, and was unable to observe this portion of the study session.

It is important to note that the researcher did not control the content that was covered in any of these groups. All of the groups that were observed were self-initiated study groups that decided on their own what content to cover and how to go about studying. Each group would have met regardless of the researcher’s presence or absence.

The researcher made every effort to remain as a detached observer of the group. This meant that she did not initiate content-related conversations with the members of the groups, as it was not the intention to influence the way that students interacted with the content. This did not mean, however, that the researcher would not interact in any way with the students in the study groups. We found it important to try to build some sort of rapport between the students and the researcher. Especially in the cases where the students had no prior relationship with the researcher, some small conversation and
introductions were necessary. We suspect that this interaction also helped to foster further invitations from group members to observe additional study sessions.

Most groups were self-sufficient and only interacted minimally with the researcher. There were some groups, however, that encountered difficulties while they were studying and turned to the researcher for additional assistance. In these circumstances, help was provided to the groups, and when students asked questions, we provided assistance in the form of explanations. As a graduate student interested in the field of organic chemistry and a TA for the lab course, the researcher was able to provide (in most cases) reasonable responses to the students’ questions. This expertise and help was valued by the students studying organic chemistry, although in some cases, this expertise was valued too much. There were a fraction of groups that relied heavily on the researcher for information, which made it difficult to know how these groups would have behaved in absence of the researcher. In such cases, the study sessions turned into ask-and-answer sessions, where the researcher provided any requested information. For this reason, sessions in which the researcher contributed 15% or more to the content-related discussion were not considered for analysis. This constituted six of the study sessions that were observed. The remaining 34 study sessions (from 14 distinct study groups) were analyzed for use in this study.

Study sessions were observed as frequently as possible. We tried to make every effort to make observations throughout the semester, and particularly encouraged groups to invite the researcher to observe their group multiple times. This was not always possible, as schedules occasionally conflicted or the researcher was unable to attend. In
other cases, the study groups did not invite the researcher back to make observations, or the groups did not meet more than one time. A total of 14 distinct study groups were observed, and the number of observations made totaled 34. Seven of the groups were observed only once, but others were observed multiple times. Three groups were observed twice, two groups three times, one group five times, and one group ten times. This last group in particular was observed multiple times, and it would be worth mentioning that this was a unique case. The student who organized this group was highly motivated to study with other students. She organized study sessions that met regularly and invited her entire class to participate. She had an open invitation that attracted a variety of students to her study sessions—some that knew her and some that did not. Her instructor was invited and made an appearance on at least three occasions to help answer questions. This group was unusual in the fact that it was so public (anyone was welcome to participate), and in the fact that attendance varied dramatically; although this group was observed for a total of ten sessions, the majority of students who attended these study sessions came only once. Also, the total number of students attending each study session was often higher than in other groups. A common size for other groups was between three and five students; however, for this particular study group, the number of students in attendance at one time got as high as fifteen.

Observations were made throughout the semester as we tried to get a perspective for how students studied at different points in the course. Generally, students seemed to meet in preparation for a specific exam, and so we kept track of which exam each group was preparing for. This information can be found in Table 2.1. Most observed study
sessions met in the first half of the semester, although we were able to observe groups in preparation for each of the four unit exams, as well as the comprehensive final exam.

Table 2.1. Percentage of study sessions observed for each exam in the first semester of Organic Chemistry, as measured by the average number of total sessions observed pertaining to each exam

<table>
<thead>
<tr>
<th>Exam Number</th>
<th>Target Content</th>
<th>% Sessions Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>Naming compounds using IUPAC nomenclature, translating representations (ex. condensed and Lewis structures), identifying hybrid orbitals, drawing structural isomers and resonance structures, drawing simple mechanisms, predicting acidity/basicity trends.</td>
<td>35.3%</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>Identifying types of stereoisomers, labeling stereocenters as “R” or “S,” translating between methods of representation (ex. Fischer and Newman projections), predicting the most stable chair conformation, classifying general types of reactions.</td>
<td>23.5%</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>Predicting the product of reactions involving alkene or alkyne reactants, proposing mechanisms involving functional group transformations, proposing synthetic pathways.</td>
<td>17.6%</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Differentiating between substitution and elimination reactions, predicting the product of organometallic reactions, proposing mechanisms and synthetic pathways, using spectroscopy (such as NMR, IR, or mass spectroscopy) to predict the structure of a compound.</td>
<td>17.6%</td>
</tr>
<tr>
<td>Final</td>
<td>Comprehensive (all of the above).</td>
<td>5.9%</td>
</tr>
</tbody>
</table>

Often when students met to prepare for the final, they studied by focusing on content from one specific exam earlier in the semester. For cases such as these, we grouped these sessions with the representative exam for which they were studying. Those groups that we did categorize as studying for the final exam prepared by using
content from across several exams in the semester. Primarily, these groups were using content from the third and fourth exams to prepare for the final.

**Analysis of Data**

Audio recordings were transcribed and carefully analyzed using an iterative, non-linear comparison method in which different types of interactions and content processing were identified (Charmaz, 2006). Transcriptions were first examined in order to identify the episodes in which students were on-topic and discussing chemistry content. Segments where students were off-task or discussing non-content related aspects of the course were not used as part of the analysis. Results from prior studies on classroom interactions were used to develop a list of initial codes that helped identify different types of social interactions (Chi, Roy & Hausmann, 2008; Scott & Mortimer, 2005; Volet, Summers & Thurman, 2009a). These initial codes were iteratively modified, collapsed, or redefined based on the analysis of the transcripts. Codes were developed to reflect who in the groups guided discussion by asking questions, providing information, or generating explanations. Additionally, a revised Bloom’s taxonomy (Krathwohl, 2002), was used as a framework to generate an initial list of codes for different levels of content processing. This coding system was revised and expanded to reflect specific types of reasoning that students demonstrated while discussing organic chemistry (e.g., mechanistic and synthetic analysis). A further description of the coding system that was used can be found in Appendix B.

Codes were applied at the episodic level. That is, codes were assigned every time there was a shift in either the type of group interaction or the cognitive level of the
discussion. The segmentation of the transcripts and the codes assigned to each segment were reviewed by a second researcher, who either agreed with the assignations or proposed alternative segmentations or codes. Discussion of ideas helped to refine the coding system and identify the boundaries between segments. Once agreement on segmentation and definition of codes was reached, the transcripts were coded until disagreements were lower than 10% of the total segments and codes. The resulting coding system was then applied by one researcher in order to analyze the rest of the data.

In order to compare between study sessions, the length of an episode was determined by counting the number of words spoken during that segment. In some instances, conversations between students would involve long pauses. At the same time, other sessions included students who would rapidly respond to one another, and sometimes overlapping conversations ensued. Keeping track of the number of words rather than a span of time allowed us to better capture the comparative length of different episodes. The relative frequency of different codes was determined by finding the percentage of words that corresponded to each code within the different study sessions and then averaging these values.

Limitations to Research Methodology

Only one researcher was present to make observations, which meant that some details went unrecorded and perhaps unnoticed. When students were working individually, it was impossible to record all of the structures that every student wrote down. Also, in some cases there were so many voices speaking that it was difficult to differentiate speakers or to even hear everything that was being said. In some of the
larger groups (for example, the group with fifteen members), the students split off into smaller groups of two or three. For the purposes of this research project, we were only able to record what one subset of the larger group was working on. For this reason, there were some aspects of the groups that could not be captured fully.

Additionally, because only one researcher was present at the study groups, the collaborating researcher likely did not have the same perspective that the author did. Because she had observed the groups in person, she had a context with which to interpret the transcriptions. Contextual clues such as tone or intent of students were not easily conveyed in the transcripts, and so the second coder had a slightly different perspective than the author did. It is possible that the interpretation of the transcripts is biased by this one perspective, although it is the hope that this bias was tempered by careful discussion and application of the agreed-upon coding system.

A total of 44 study sessions were observed, although only 34 of these were used for analysis. In six of the sessions, the author spoke frequently and contributed to more than 15% of the total words spent on content. Three more groups were removed from analysis, because they had not been observed for a long enough period of time in order for the researcher to have a good perception of how the students were studying. This included groups where the students worked individually and said hardly anything to one another or one group which only met for about ten minutes before disbanding. Finally, one group was removed from analysis, because the students were predominantly discussing content related to their lab exam, rather than their lecture material. This means that almost a quarter of the study sessions observed was found to be inappropriate
for analysis. The problem with this statistic is that it suggests the possibility that certain populations of students were underrepresented in the research project. For example, it is likely that the author had higher rates of participation and helping activities in those groups where the students were less prepared and less familiar with the content. These groups which represented a less knowledgeable demographic of students may have been disproportionately removed from analysis because of the greater influence of the author within those groups.

Students were not required to attend discussion sessions, and it is likely that only a portion of students enrolled in the lecture course were present during recruitment at the discussion sessions. Additionally, the organic chemistry lab is associated with the lecture course, although it is not mandatory to take both classes simultaneously. For this reason, it is possible that a certain population of students who only attended the lecture course but not the lab or discussion sessions were never given the opportunity to participate in this research project. This may have precluded certain populations from being involved in the study.

Generalizability to students outside of the University of Arizona is also uncertain. Differences in course design, instructor effect, or student populations have not been thoroughly investigated, and these factors could have influenced the manner in which students met to study and review chemistry content.

Results

The results have been organized according to the research questions of our study. We will first describe students’ methods of social regulation within their study groups,
and then describe the characteristic types of content processing. Finally, we will discuss some of the factors that affected these two dimensions of the study group.

**Social Regulation**

Participants in the study groups engaged in several forms of social regulation, ranging from individual regulation (where one student introduced and discussed content) to co-regulation by several group members (where many students collaboratively introduced and discussed content). In particular, we identified three major forms of social regulation which we are calling **teaching**, **tutoring**, and **co-construction**.

Within the **teaching** interaction, a stratification of roles existed between group members, where one student provided information, and others acted as recipients of this information. It was the person who taught the other group members who determined the information that would be addressed. Often this teaching took the form of a lecture, where one person spoke exclusively, and other group members were passive recipients of the information. The students in this latter role did not regulate their own learning by asking questions or requesting clarification. For those engaging in the **tutoring** interaction, there were also specific roles to which group members conformed. Again, there was one student who provided information to the rest of the group members, but in this case, the content that was discussed was determined by questions that were asked by other group members. The students who sought information directed the flow of conversation by asking questions, checking for understanding, and using other members of the group as resources. Other students in the group, in turn, answered questions, provided information, or corrected misunderstandings as applicable. The **co-construction**
interaction occurred when two or more students took on equivalent roles while attempting to come to a consensus regarding their understanding of a topic. These students were brainstorming, building ideas, or using one another as resources. The important features of this interaction were that several students participated in generating a mutual understanding, and that the roles of the students involved were relatively equal.

Students would shift between different types of interactions during a session or during the discussion of a single problem. In general, study groups would engage in each of the three types of interactions (teaching, tutoring and co-constructing) during a study session, although to varying extents (see Table 2.2). In this sense, some groups would rely on one interaction almost exclusively, while others engaged in each of the three indicated types of interactions at relatively equal rates. Overall, when we averaged the number of words pertaining to each interaction within the different study sessions, we found that 34.7% (SD 21.1%) of the interactions came from teaching, while 35.4% (SD 16.8%) came from tutoring, and 29.9% (SD 19.1%) were based on co-constructing.

<table>
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<tr>
<th>Group</th>
<th>Session (# participants)</th>
<th>% Teaching</th>
<th>% Tutoring</th>
<th>% Co-Construction</th>
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<td>23.2</td>
<td>43.8</td>
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<tr>
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<td>12.5</td>
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<td>51.0</td>
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<td>2 (3)</td>
<td>16.0</td>
<td>52.3</td>
<td>31.7</td>
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</table>
Teaching Interaction

The teaching interaction was most common for nine of the 34 study sessions that were observed and the least common for 15 of the sessions (Table 2.2). During each of the occurrences where the teaching interaction was observed, students would take on one of two distinctive roles. It was generally found to be the case that the students had varying rates of participation within a study group, but this was especially true when high levels of teaching were observed. Those who took on a teaching role had much higher rates of participation than the rest of the students in their group. When students taught each other, 79.2% (SD 11.9%) of the words originated from one or more individuals giving explanations or presenting information, while 20.8% of the words came from other group members responding to this information with comments or questions. Our analysis of the groups that predominantly engaged in the teaching interaction yielded two formats from which groups participated through teaching.

It was most common for groups that engaged in the teaching interaction to have specific individuals present who led the group through instruction by making decisions on what to study and providing explanations to the rest of the participants. In these situations, the role played by each member of a group (either as traditional “teacher” or “student”) tended to remain unchanged within and across study sessions. For example, in the following excerpt, two students (O and K) were working to name an organic compound (Figure 2.1). Student “O” took on the role of teacher by creating his own examples of molecules which he used to model different ways of naming compounds. He shared his thought process and reasoning behind each example. His role stayed
consistent throughout the study session that was observed, as he continually worked to provide examples and explanations for his study partner.

![Structure of organic compound]

Figure 2.1. Structure of organic compound that was the focus of students’ self-created nomenclature problem.

O: Well we’ll go through it. We’ll go through it. Okay, so numbering system. Where do you start? (pause) So. You didn’t notice there’s a tie. Okay, so there’s a tie, 1,2,3,4. 1,2,3,4.
K: So it’s a tie so you go to this one?
O: But here you are missing one thing. So you can go to the next one, right? So it’s four here, right? Well what’s the next one? It’s like in the middle. (pause) That chain. . . So you’re gonna find the counting word, right? So it’s where the carbon, you start where it’s the first substituent, the first substituent you can get.
K: Right.
O: So this is your one substituent right here, and that’s on the end carbon, so that’s a one.
K: So you can count going the opposite way, it doesn’t matter.
O: Yeah. Left to right, right to left, it doesn’t matter. Anything attached to the mother is an inferior substituent, okay?

A second way in which students engaged in the teaching interaction was to take turns leading the group as “teacher.” In these cases, several students worked on the same problems individually and then reported back as a group, taking turns to teach the group how each person came to an answer. For each problem, one individual would address the group and explain how he or she answered the question and others would have an opportunity to add their thoughts as well. This method of teaching was less common, although we observed several instances where students would reverse their teaching roles.
within a given study session. A representative example is shown below, where one student described her process for coming up with a solution to a problem (Figure 2.2).

![Diagram of a chemical reaction](image)

Figure 2.2. An instructor-provided problem requiring students to propose the reactant and intermediate of a halogenation problem.

C: *So for this one I thought, I had to work on it looking backwards, because I saw, I looked at it backward and saw this addition, two bromines. And then you can see where they were added, but then you have to, for me I had to think where they were adding from? And what they would need to be added. Like, what would need to be there in order for them to be added. And that’s how I found this starting material. Because I knew that we were going to have to make this vicinal bromine. Coming from the double bond, which is between this one.*

In instances such as these, students reflectively shared the thought processes that led them to a solution. The student above, for example, shared her methodology (“looking backward”) as well as the features that she paid attention to (“Because I knew that we were going to have to make this vicinal bromine”).

**Tutoring Interaction**

Tutoring was the most common type of interaction for 15 of the 34 study sessions, while being the least common for five of the sessions (Table 2.2). The students who engaged in the tutoring interaction had specific roles. That is, predominantly either asked questions of their group members, or spent time answering questions. There was little
deviation in these roles throughout the study session. Contributions to group talk as measured by word counts were equally divided between these two types of participation, with 48.8% (SD 11.6%) of group talk coming from individuals asking questions, and 51.2% of group talk corresponding to students answering questions.

Analysis of groups that exhibited tutoring interactions at the highest rates showed that groups tutored using one of two formats. The groups that spent the highest proportion of time engaging in the tutoring interaction were likely to spend a significant portion of their study session working individually. These students worked independently, with the students of some groups even working on different material than the other members of their group. When these students came to a problem that they did not understand, they would turn to their group members and ask a question. For example, in the excerpt below, one student had been working independently, though she turned to her study partner to ask a question when she realized that there was an aspect of her notes that she believed to be inconsistent (Figure 2.3). In general, students exhibiting tutoring interactions in this way had relatively short exchanges.

![Figure 2.3](image)

**Figure 2.3.** A student’s notes regarding an oxidation reaction which included an inconsistency in the intermediate and final product.

*S:* So for this one? In my notes? There’s an extra carbon in the final. Like see that extra little methyl sticking out?

*A:* There’s an extra?

*S:* Yeah, see how there’s five and then there’s six? It’s in my notes.
**A:** Hold on. (looking through her notes) Ozonolysis. Yeah, that methyl shouldn’t be there. So it doesn’t matter what you have, you could have some crazy thing with 14 of these [double bonds], and you just keep cleaving it. You just add one for every time there’s a double bond.

Students’ engagement in the tutoring interaction could also be classified into a second, less common format. The students in this category worked in a collaborative rather than independent manner, with the entire group discussing each problem or question together. As shown in the following excerpt, in this latter case it was common to have more students taking the roles of questioner than of answerer. Multiple parties would collaboratively construct questions pertaining to a similar topic, while another student (or students) would attempt to answer these questions. In the following example, Student “K” fielded questions about the halohydrin reaction, while many of her group members (A, C, and N) collaboratively discussed and posed questions to the group. Many of their questions built off of one-another as they worked to understand different aspects pertaining to this reaction.

**A:** On the halohydration one, don’t they go on opposite sides?

**K:** Halohydrin?

**A:** Halohydrin, yeah.

**K:** It’s syn addition. Not anti addition.

**C:** So they’re on the same side?

**A:** So we don’t need to know anti addition?

**N:** So of addition? There’s syn and anti addition?

**K:** You need to know anti addition. Anti addition happens in halogenation.

**N:** Is that right? There’s like, the addition and substitution, duh duh duh. And for the addition? There’s syn and anti? Okay, can we go over that?

**C:** But couldn’t syn also happen for the halogen, the . . .

**K:** Halogenation? It doesn’t. Trans is more stable. That’s why anti addition happens.
Co-constructing Interaction

The co-construction interaction was most common for 10 out of 34 of the study sessions but least common for 14 of the sessions (Table 2.2). We analyzed the groups with the highest proportion of co-construction interactions in order to determine the common qualities for groups that interacted in this way. When students co-constructed, they tended to do so in groups that were relatively small in size, with only two to three students involved in the interaction (the average group size was closer to five students). The participants in these groups discussed problems collaboratively as the students worked together, all focusing on the same problem at the same time. There was no difference in roles between participants, as each contributed in a similar way to the co-construction interaction. It was also common for groups to use a whiteboard on which to write the problems, which was a useful tool in facilitating a whole group discussion of what the solutions should look like. The whiteboard allowed for all of the participants to see the chemical structures being referenced. Students seemed to engage in co-construction when no one in the group was able to provide the answer to a problem without the help of their group members. The students tended to turn to this interaction when there was no readily available explanation from any one student. For example, in one study session, the students collaboratively discussed the possible steps in a synthesis problem when no individual was able to solve the problem on his or her own (Figure 2.4). The way that students A, P, and H interacted in this excerpt is representative of the co-construction interaction.
A: Alright, so OCH$_3$ is . . . would you have to draw that as a leaving group? Like OTs?
P: OMe?
A: You have to get back to the triple bond somehow. Yeah, so is that a leaving group?
P: Yeah.
A: It is?
H: Are you guys going backward?
P: Yeah.
A: Okay, so.
H: Could you do like a NaOCH$_3$ or like in the parenthesis, OCH$_3$, close parenthesis 2CuLi? Do you get that? If that makes sense?
A: No. Hold on, let me think real quick. Okay, so you have the OCH$_3$. So that got added on. So write that out. Just write OCH$_3$ on the last thing somewhere. That got added. What would it have been added with? Base. Some sort of base.
P: Why?
A: Because that would bring us back to at least a double bond, right?
P: Yeah.
A: A big base.
P: Do you think there was a double bond?
A: There has to have been.

Overall, students worked with one another in several different ways, and the major trends of students’ behavior could be characterized through the categories of teaching, tutoring, and co-construction. There were several groups that used one interaction to the exclusion of others, but there were many that engaged in all three types of interactions with relative equivalency throughout their study sessions. For these
groups, there are aspects of their study sessions that can be described by the different interaction categories, although they were not likely to fall into a single category.

**Content Processing**

The independent student study groups that were observed primarily studied by working through problems either as a group or individually. Most of these problems were generated by their instructor (for example, in the form of a practice exam), or were suggested for students to work from (textbook problems). Most groups worked at least part of the time from these types of instructor-provided problems, and overall, groups spent about 63.6% (SD 36.9%) of their discussion focused on these instructor-provided problems (as measured by the average number of words that each study session devoted to this type of prompt). Students would also work from self-generated problems, and this represented an average of 13.0% (SD 29.4%) of their discussion. Additionally, students would form questions that were the basis for discussion, and in these cases, students broached queries unrelated to other content on which they were working (10.0%, SD 14.8%). Finally, some groups reviewed material from their notes or from an instructor-provided list of reactions (13.4%, SD 29.4%). The analysis of their conversations in these different formats revealed the following main levels of content processing:

— **Remember**: Students retrieved relevant information from long-term memory and used it to, for example, define concepts, recall values, identify categories, or recognize processes in order to solve a problem or answer a question. On average, content was discussed at this level during 35.7% (SD 13.6%) of group conversation.
— Understand: Students tried to determine the meaning of concepts or ideas by, for example, interpreting chemical representations, comparing chemical processes, building inferences, and explaining ideas (Average 13.0%, SD 11.2%).

— Apply: Students used their knowledge to solve a problem following two main approaches:
  - Executing: carrying out a well-established set of procedures (Average 22.3%, SD 23.7%).
  - Implementing: more freely applying learned principles without the use of an algorithm or set of rules to follow (Average 11.6%, SD 12.7%).

— Analyze: Students broke down information into parts in order to detect how the different components related to one another. Multiple factors were considered in order to interpret a problem. At this level, we differentiated content-specific methods of analysis:
  - Connect-the-dots: Students created reaction mechanisms based on structural differences between reactants and products (Average 2.69%, SD 7.51%).
  - Mechanistic: Students created reaction mechanisms using chemical principles to propose a sequence of events (Average 2.56%, SD 5.68%)
  - Synthetic: Students compared structural differences between products and reactants to propose reaction conditions or synthetic pathways that would accommodate these differences (Average 2.43%, SD 6.95%)
  - Generic: Students used generic procedures to analyze chemical structures and processes (Average 8.56%, SD 14.6%)
— Create: Students put together information in order to generate an answer, for example inferring the structural formula of a chemical compound from different types of spectroscopic data (Average 1.03%, SD 4.10%).

The extent to which students engaged in these different levels of content processing varied among the different study groups and study sessions. Average results for all of the study groups are presented in Table 2.3 (and Figure D.1), where the percentage of content-related words associated with different levels of content-processing are separated based on the different type of social regulation process in which students were engaged. In general, over 80% of the observed content-related conversations corresponded to lower levels of content processing in our coding system (remember, understand, and apply) regardless of the nature of the social interactions. The analysis of the data revealed the existence of nuanced relationships among types of social regulation, levels of content processing, and other contextual factors.

<table>
<thead>
<tr>
<th>Levels of Content Processing</th>
<th>Teaching Avg % (SD)</th>
<th>Tutoring Avg % (SD)</th>
<th>Co-construction Avg % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remember</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg % (SD)</td>
<td>34.7 (28.3)</td>
<td>49.1 (27.5)</td>
<td>32.0 (23.5)</td>
</tr>
<tr>
<td>Understand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg % (SD)</td>
<td>9.36 (11.5)</td>
<td>16.1 (17.2)</td>
<td>9.76 (15.6)</td>
</tr>
<tr>
<td>Apply</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Executing</td>
<td>28.4 (35.9)</td>
<td>14.4 (18.5)</td>
<td>20.4 (19.9)</td>
</tr>
<tr>
<td>Implementing</td>
<td>8.31 (14.4)</td>
<td>9.94 (15.8)</td>
<td>17.8 (20.1)</td>
</tr>
</tbody>
</table>
Influential Factors

Study groups that were observed demonstrated varying types of social interactions and levels of content processing. Many groups were consistent throughout a particular study session, though in certain cases, they would deviate from their normal course due to either a change in content-related factors or social-related factors. We sought to characterize these factors to better understand when and why students altered their patterns of interactions or changed their level of content processing. Given the central role that solving chemistry problems had on the groups’ approaches to studying, the specific content and structure of such problems had a strong influence on the level of content processing and the type of social interactions among study session participants. However, the effect of task features on group work was mediated by a group’s decisions about the organization of the study session and by the different levels of content knowledge and conceptual understanding of the various attendees.
Group Composition Features

Two group composition features seemed to affect how students interacted with one another and with the organic chemistry content. These features included the group’s method of organization as well as the relative expressed content knowledge of students within a group. Students’ decisions about how to organize a study session frequently imposed constraints on the nature of group interactions. For example, students who studied by working individually, rather than collectively, often relied on tutoring as their main form of interaction. Students in these groups worked at their own pace on individual tasks, and the communication between group members was often brief and shallow. Students who worked by themselves on a task would interact one-on-one with other group members by asking questions about specific aspects of a problem, rather than requesting the group members to help them solve the entire problem together. They would often request factual or procedural information, and as a result, the tutoring interaction was correlated to lower levels of content processing compared to either co-construction or teaching (Table 2.3).

Groups were also influenced by the relative content knowledge expressed by the students within the groups. Study sessions which included one or more individuals who appeared to have a deeper understanding of the chemistry concepts often exhibited higher levels of the teaching interaction. In some cases, when one of these individuals joined a group in which the students had been working individually, this person would focus the group’s attention and facilitate a shift to a teaching interaction. For example, in one case, a group was working individually and predominantly tutoring one another (58.2%
tutoring interaction). Partway through the study session, their instructor arrived and began to help them with their studying. This resulted in a shift toward the teaching interaction, which accounted for 86.4% of the discussion after his arrival. Additionally, although many group members had been speaking prior to this, the instructor contributed 84.0% of the words that were spoken after he joined the group. It was common to see individuals such as this instructor, or students who appeared to have greater expressed content knowledge, make large contributions to group discussion, such that participation from other students appeared to be suppressed. These individuals tended to have a disproportionate influence over the rest of their group members. When they joined a study session, these individuals seemed to affect both the interactions that other students engaged in, as well as the rates of participation among group members.

In fewer occasions, a difference between the levels of understanding among group members contributed to higher rates of the tutoring interaction. In these cases, the student who appeared to be more knowledgeable fielded questions from multiple group members. The students in these groups participated in a shared activity where the “tutor” facilitated the discussion and addressed questions. Study group 8 was an example of a group where one student (K) tended to lead the group discussion through either a teaching or a tutoring interaction (Table 2.2). For most of the observed sessions, student “K” played a dominant role in the group and acted as an expert by providing information and acting as a resource to other students. A shift occurred during one study session in which “K” was unable to attend. During this study session, other members in the group who had previously contributed only minimally to the discussion were now the main
participants. At this session, these students had higher rates of contributions, and additionally, they had new opportunities to create their own explanations and to teach their group members new information.

The presence of a knowledgeable person in a study session tended to increase the level of content processing that was observed, although it also tended to suppress the contributions from other students in the group. Most of the explicit analysis was done by the “teacher” or “tutor” in the group with little contribution from other participants. It was only when the more knowledgeable individual was absent that other students had the opportunity to more actively participate in the construction of knowledge.

The co-construction interaction was most common in small groups or sub-groups of students (between two to three) when working collaboratively as a group. Co-construction was elicited when no one in the group was able to solve a selected problem individually. For this reason, a group that was predominantly tutoring or teaching could shift to a co-construction interaction if they came across a problem that proved to be difficult for all group members.

An example came from a study group that was being facilitated by one student (E) who was contributing to the group through a teaching interaction. Yet when the group began solving a problem that concerned a Fischer projection, all students (even E) appeared to have greater difficulty solving this problem. No one was able to answer the problem immediately on their own, and it took some time before the group was able to work out the solution. Because no one in the group was familiar enough with the subject matter to explain the necessary concepts to the other group members, the interaction
shifted to co-construction during discussion of this problem. Prior to this problem, the students were primarily interacting through a teaching interaction (61.6% of their words) while co-constructing and tutoring to lesser extents (19.4% and 19.0% of their words, respectively). When the group approached the more challenging Fischer projection problem, they shifted to a co-construction interaction (58.5% of words). The extent of their tutoring and teaching interactions both decreased during discussion of this problem (2.2% and 39.3% of words, respectively). This example illustrates how a common lack of understanding initiated a change in student interactions. Generally, when there was no one in the group who was able to come up with an explanation for a topic, the group would turn to the co-construction interaction in order to collaboratively discuss the concept. The level of content processing in these situations was largely determined by the specific content and structure of the study problems that were being addressed.

Task Features

A change in a problem or topic would often elicit a change in student interactions or level of content processing. As the semester progressed, students focused on different topics (Table 2.1) and the levels of content processing exhibited in study groups changed as a result. Overall, groups tended to become more diverse in their levels of content processing, and they tended to trend toward higher levels (such as analyze or create) as the semester advanced. Table 2.4 demonstrates the levels of content processing that pertained to each exam, as measured by the average percentage of words that each group spoke at the different levels of content processing (data are also presented in Figure D.2).
Table 2.4. Levels of content processing in study groups as demonstrated across each unit exam

<table>
<thead>
<tr>
<th>Exam Number</th>
<th>Remember Avg % (SD)</th>
<th>Understand Avg % (SD)</th>
<th>Apply Avg % (SD)</th>
<th>Analyze Avg % (SD)</th>
<th>Create Avg % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exam 1</td>
<td>34.1 (14.0)</td>
<td>11.5 (12.1)</td>
<td>49.5 (31.6)</td>
<td>4.81 (13.4)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Exam 2</td>
<td>45.1 (12.0)</td>
<td>12.5 (6.64)</td>
<td>31.2 (14.9)</td>
<td>11.1 (7.23)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Exam 3</td>
<td>36.3 (18.2)</td>
<td>9.44 (11.6)</td>
<td>25.1 (16.1)</td>
<td>29.1 (10.5)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Exam 4</td>
<td>25.1 (6.20)</td>
<td>22.6 (10.6)</td>
<td>20.0 (11.1)</td>
<td>26.4 (6.98)</td>
<td>5.82 (8.81)</td>
</tr>
</tbody>
</table>

In the beginning of the semester, students worked on tasks that required them to do such things as give the chemical name of an organic compound or to identify structural features in a chemical compound. These tasks traditionally triggered lower levels of thinking (remember or apply) than problems that asked them to design a synthetic pathway or to infer a chemical structure from different sources of spectroscopic data (tasks that became more common later in the semester). Some students tried to simplify the solution to a complex task by searching for and applying standard algorithms or procedures (executing), although in general, a higher cognitive demand from a problem elicited a higher level of content processing from those students involved in generating the answer.

Certain problems elicited specific levels of content processing and types of student interactions. For example, problems that required students to construct a synthetic pathway were likely to invoke higher levels of synthetic analysis, and this generally occurred through a co-construction interaction (Table 2.3). We found that 71.9% of words that students spoke at the synthetic analysis level came from a co-construction interaction. The students that we observed were generally unable to
individually solve a synthesis problem within a limited amount of time, leading them to rely upon other group members as they collaboratively co-constructed in order to design a synthetic pathway.

Similarly, as students worked on problems which required them to interpret NMR data, they tended to interact in particular ways. Specifically, this type of problem was the only prompt that elicited discussion at the “create” level of content processing. In this case, the majority of words (68.8%) that came from the “create” level originated from students who were teaching each other. When working on this type of problem, whole groups of students were sometimes involved in the analysis process of interpreting the NMR data; however, once the groups had inferred different isolated pieces of information about a structure, they would have difficulty synthesizing this information. At this point, an individual might take over to teach the other students by explaining how to interpret the information they had gathered in order to infer the structure of a compound (create). For example, in the excerpt below, student “K” taught her group members how she would use all of the information available from spectral data in order to infer the structure of a chemical compound (CH₃COCH₂CH₃).

*K:* So you have a singlet representative of three hydrogens, and you know you have this carbonyl somewhere. Well if you put a methyl group on the end, this isn’t going to have any neighbors, as long as it’s not attached to any other carbon. Right? So there’s your singlet. And then, so, like subtraction, just subtract what you’ve used so far from this formula and see what you have left. You have C₂H₅.
*B:* Okay. So I have two more Cs, and—
*K:* And five more hydrogens. And then you know you have something that represents three hydrogens and something that represents two hydrogens.
*B:* Ohh!
*K:* Yeah! CH₂ and CH₃. And then you use the splitting to check. I would say, use the splitting to check. Like see how this is a quartet and this is a
triplet. Well the quartet is representative of the 2H, so look at the 2H right here.

The above examples indicate that there was a relationship between the task from which a student worked and the types of social interactions as well as levels of content processing that came as a result.

There were several different types of prompts from which students generated their discussion of organic chemistry. A small portion of content-related conversation in the observed study sessions originated from students’ questions or from the review of course material (exhibited by 12 and 20 of the 34 groups, respectively). Conversation from both of these sources tended lead to lower levels of content processing (Table 2.5 or Figure D.3), as measured by the average percentage of words spoken at each level. The most common way for students to study was to work from problems: either problems that were suggested by course instructors (exhibited by 28 of the 34 groups), or those that were self-generated by the students (created within 12 of the 34 groups). These latter types of problems tended to be less difficult and elicited lower levels of content processing (Table 2.5). Student-created problems also led to a comparatively shorter length of discussion for each problem, as students spent about 60% more words discussing each instructor-provided problem compared to the self-created problems from which they worked. Overall, instructor-provided problems resulted in the greatest length of discussion and the highest levels of content processing, compared to any other type of prompt from which students may have worked.
Table 2.5. Discussion prompts and the levels of content processing that correspond to each type of prompt.

<table>
<thead>
<tr>
<th>Type of prompt</th>
<th>Remember Avg % (SD)</th>
<th>Understand Avg % (SD)</th>
<th>Apply Avg % (SD)</th>
<th>Analyze Avg % (SD)</th>
<th>Create Avg % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instructor Problem</td>
<td>29.3 (26.6)</td>
<td>12.9 (12.1)</td>
<td>36.7 (37.5)</td>
<td>19.6 (41.8)</td>
<td>1.45 (5.32)</td>
</tr>
<tr>
<td>Student Problem</td>
<td>54.7 (58.1)</td>
<td>3.58 (8.52)</td>
<td>36.1 (43.6)</td>
<td>5.54 (19.2)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Student Question</td>
<td>68.9 (67.3)</td>
<td>19.4 (28.7)</td>
<td>11.5 (30.5)</td>
<td>0.224 (1.00)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Review Task</td>
<td>62.8 (76.4)</td>
<td>19.2 (22.4)</td>
<td>14.5 (34.1)</td>
<td>3.49 (7.69)</td>
<td>0.00 (0.00)</td>
</tr>
</tbody>
</table>

The difference in depth of discussion between self-created and instructor-provided problems might be explained by the divergence in types of problems that were posed: the types of problems that students created were not always similar to the types of problems that were provided to them by their instructors. There were only four categories of problems that constituted overlap between those problems posed by students and those posed by their instructors. These four types of problems included:

1. Predicting a product as a result of given reaction conditions (which accounted for 23.0% of all instructor-provided problems and 38.6% of all student problems)
2. Naming an organic compound (14.9% of all instructor and 9.09% of student problems)
3. Predicting the structure of a compound that acts as both a product and reactant in a partially completed synthesis reaction (1.70% of instructor and 6.80% of student problems)
4. Proposing a synthetic pathway (2.98% of instructor and 2.27% of student problems)

When we compared these common problems, we saw that even between similar types of problems, a disparity existed between the responses that were elicited from student-created versus instructor-provided problems. Instructor-provided problems were likely to elicit higher levels of content processing even within the same category of problem. Table 2.6 shows the levels of content processing associated with each type of problem relative to the source of the problem (also shown in Figure D.4).

Table 2.6. Levels of content processing which students engaged in for each of four different types of problems proposed by instructors or created by students.

<table>
<thead>
<tr>
<th>Common Problems</th>
<th>Remember Avg % (SD)</th>
<th>Understand Avg % (SD)</th>
<th>Apply Avg % (SD)</th>
<th>Analyze Avg % (SD)</th>
<th>Create Avg % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Predict Product</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instructor Prob. (n = 53)</td>
<td>39.8 (41.8)</td>
<td>12.8 (27.7)</td>
<td>23.1 (35.2)</td>
<td>24.4 (38.8)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Student Prob. (n = 17)</td>
<td>78.7 (37.4)</td>
<td>5.56 (23.6)</td>
<td>15.7 (32.0)</td>
<td>0.00 (0.00)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td><strong>Name Compound</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instructor Prob. (n = 33)</td>
<td>29.5 (39.5)</td>
<td>8.38 (23.5)</td>
<td>62.2 (43.3)</td>
<td>0.00 (0.00)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Student Prob. (n = 4)</td>
<td>6.89 (8.09)</td>
<td>0.00 (0.00)</td>
<td>93.1 (8.09)</td>
<td>0.00 (0.00)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td><strong>Predict Product/Reactant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instructor Prob. (n = 4)</td>
<td>18.0 (23.0)</td>
<td>13.0 (25.9)</td>
<td>29.8 (47.7)</td>
<td>39.2 (48.6)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Student Prob. (n = 3)</td>
<td>70.6 (34.6)</td>
<td>0.00 (0.00)</td>
<td>12.2 (21.1)</td>
<td>17.2 (15.8)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>----------------------</td>
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</tr>
</tbody>
</table>

**Propose Synthesis**

<table>
<thead>
<tr>
<th>Instructor Prob. (n = 7)</th>
<th>8.01 (11.1)</th>
<th>11.5 (26.9)</th>
<th>17.7 (23.7)</th>
<th>62.8 (36.1)</th>
<th>0.00 (0.00)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student Prob. (n = 1)</td>
<td>28.8 (N/A)</td>
<td>29.9 (N/A)</td>
<td>0.00 (N/A)</td>
<td>41.3 (N/A)</td>
<td>0.00 (N/A)</td>
</tr>
</tbody>
</table>

For three of the four common types of problems (all but naming an organic compound), the instructor-provided problems elicited higher levels of content processing than did student-created problems (Table 2.6). Even though the problems were of a similar structure, the discussion that came as a result was of a different quality. One reason for this has to do with the subject matter that was discussed. For example, when students worked on problems that required them to predict the product of a reaction, the types of reactions that they considered varied depending on whether they were working from student-created or instructor-provided problems. Student-created problems under this category primarily came from study sessions prior to the third exam, for which reactions involved simple functional group transformations. These types of problems were less sophisticated than the instructor-provided problems that were primarily seen in preparation for the fourth exam. When students had to predict products for these reactions, they needed to consider many competing factors in order to differentiate between substitution and elimination reactions. In this way, the context for which students were studying affected the depth to which they discussed their problems. The
student-created problems were often less sophisticated than the instructor-provided problems, and this affected the depth to which students discussed the material.

A second explanation for why similar student-created problems elicited lower levels of content processing comes from the interactions of students within the study groups. When a student posed a problem to his or her group, this student would generally already know the answer to the problem. This meant that when other group members were unsure of the answer, it could easily be resolved by the student who created the problem. For example, in the excerpt below, student “L” posed a problem for “C” who was asked to predict the product of a reaction (Figure 2.5). “L” already knew the answer, and was easily able to step in when there was not an immediate response from the group member that he was quizzing.

Figure 2.5. A student-created problem which required the respondent to predict the product under given reaction conditions.

C: Okay, give me another reaction. (L writes above problem on the board) Does that put the OH in the (unintelligible) position?
L: So. This one, you’re going to get a bromine out of this. Bromine there. And then a methyl here, an OH there. Yeah. So that they add anti to each other, so OH has to be back, bromine has to be forward. Or bromine could be back, OH could be forward.
C: Wait, what does anti mean again?
L: Anti is, so these two are the ones are added, and anti means one was added forward, one added back. And then these guys have to add syn.
In this example, student “L” stepped in to answer the problem before “C” had a fair chance to reason out the solution. He appeared to answer simply by memory, and did not need to rely on deeper strategies in order to find a solution. In general, for most groups that worked from student-created problems, it was not necessary for the students to go to a very deep level to try to reason through the solution. If the rest of the group was having difficulty answering a problem, the student who posed the question would step in and explain it to them. This example demonstrates another key aspect about the differences between types of prompts that students worked from, in the sense that different sources of discussion were facilitated by different types of social regulation. Discussion that resulted from student-created problems tended to come as a result of the teaching interaction, with an average of 65.4% of words coming from this interaction (Table 2.7 or Figure D.5). On the other hand, instructor-provided problems were not dominated by any one type of interaction, although this prompt did elicit the highest rates of co-construction (35.2%) among any of the other types of prompts. Student questions were generally facilitated through a tutoring interaction (71.6%) and review of material was most frequently taught to other group members (50.4%).

<table>
<thead>
<tr>
<th>Type of Prompt (source of discussion)</th>
<th>Co-Construction Avg % (SD)</th>
<th>Tutor Avg % (SD)</th>
<th>Teach Avg % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instructor Problem</td>
<td>35.2 (19.4)</td>
<td>35.0 (19.1)</td>
<td>29.8 (17.8)</td>
</tr>
<tr>
<td>Student Problem</td>
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<td>15.0 (16.5)</td>
<td>65.4 (36.5)</td>
</tr>
<tr>
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<td>15.5 (25.1)</td>
<td>71.6 (31.2)</td>
<td>12.9 (22.6)</td>
</tr>
<tr>
<td>Review</td>
<td>30.2 (29.1)</td>
<td>19.5 (18.9)</td>
<td>50.4 (30.7)</td>
</tr>
</tbody>
</table>
Discussion, Conclusions, and Implications

This study was primarily interested in uncovering the methods of social regulation and cognitive processing that were present within self-initiated study groups in organic chemistry. We found that students regulated their study groups using three different types of interactions: teaching, tutoring, or co-construction. These three categories represent different ways in which students broached topics and shared information between group members. On average, none of these interactions was more prevalent than the others, although the extent to which students engaged in each interaction varied widely among groups and within study sessions. The variability seemed to be determined by the composition of the study groups as well as the nature of the study tasks in which they were engaged. Each group made explicit and implicit decisions about how to organize their study session. These decisions, along with the relative knowledge of the group members with respect to the cognitive level of the tasks influenced interaction patterns as well as the content processing that was observed.

The focus of group work was most commonly directed toward solving problems that had been provided or suggested by their instructors. On other occasions, groups would create their own problems to solve, discuss questions, or review topics, but these methods of studying were far less frequent. The primary method of studying exhibited by study groups was to work from suggested problem sets. Similar results have been reported in the analysis of individual college students’ approaches to studying in science (Tomanek & Montplaisir, 2004). We found that these different methods of studying resulted in varying levels of content processing. Instructor-provided problems were of
the greatest cognitive difficulty and required students to implement more diverse skill-sets, especially when compared to student-created problems of similar structure. Yet overall, students tended to discuss chemistry topics at lower levels of content processing (such as remember, understand, or apply).

The lowest levels of content processing were exhibited when students engaged in the tutoring interaction. Although the rates of participation were relatively equal for students both asking and answering questions, these students tended to focus on surface-level discussion of the content. The students who posed questions would do so to broach subjects and test hypotheses, but the responses that these questions elicited were often cursory exchanges that did not require high levels of content processing. This outcome seemed to be largely determined by the conditions that favored the emergence of tutoring interactions in the study groups. Students would engage in the tutoring interaction while working individually on problem sets. The environment through which this interaction emerged was one of individual self-involvement. Each student was preoccupied with the content that they were personally investigating. As a result, the exchanges between group members were frequently constrained to short verbal exchanges that mainly helped to clarify aspects of a problem or provide specific guidance on solution procedures. This type of sporadic interaction limited the opportunities for groups to engage in the types of tutoring activities that are known to favor high-level cognitive processing and meaningful learning, such as independent or joint construction of knowledge (Chi, Roy, & Hausmann, 2008), and creation of explanations (Roscoe & Chi, 2007, 2008).
A further reason why the tutoring interaction elicited such low levels of content processing is the type of questions that were posed between group members. If not taught differently, students tend to focus on the most concrete-levels of a subject (Cohen, 1994). As a result, the questions that students posed were of disappointing quality (Marbach-Ad & Sokolove, 2000; Offerdahl, Baldwin, Elfring, Vierling & Ziegler, 2008). If students were to ask deeper, more open-ended questions during the tutoring interaction, this may have resulted in higher levels of content processing (McNeill & Pimentel, 2009; Roscoe & Chi, 2004). From a group coordination perspective (Barron, 2000, 2003), tutoring in the observed study groups lacked many of the characteristics of productive group work.

Relatively higher levels of content processing (such as analyze or create) were exhibited by groups that tended to teach or co-construct. Within the teaching interaction, one student would predominantly contribute to a conversation by lecturing information to other group members. While this student tended to discuss information at higher levels of content processing, the presence of such a group member constrained the rates of participation of other group members. The student who would teach often offered explanations before others in the group had an opportunity to self-construct their own explanations or formulate questions about the topic. Additionally, subjects were often discussed on the basis of only one person’s decisions. Research suggests that students have a tendency to summarize information that they already know, unless interjections from others force them to consider explanations for concepts they would otherwise have not considered (Roscoe & Chi, 2007). Therefore, both parties within the teaching
interaction had limited opportunities to build new connections, construct explanations, or analyze chemistry content. The lack of mutuality in participation limited the opportunities for all of the students to meaningfully discuss the content (Barron, 2000; Scott, Mortimer, & Aguiar, 2006).

In contrast, within the co-construction interaction, all students who were involved suggested information, argued ideas, and brainstormed together. By participating in the co-construction interaction, students in these study groups actively participated in the construction of knowledge. Yet groups did not appear to intentionally structure their groups to facilitate this interaction. Rather, co-construction emerged most frequently as a last resort in trying to solve a problem. Generally, students engaged in co-construction when no one in their group was readily able to answer a problem on their own. This inability for an individual to comprehend a solution opened the door for participation from several group members. Thus, problems that required a higher level of cognitive ability (such as synthesis problems) tended to elicit a co-construction interaction.

The apparent lack of intentionality regarding students’ engagement in co-construction interactions, when compared with the more purposeful approach taken by some of the groups to organize their study sessions using a tutoring or a teaching format, may have been determined by a variety of personal and contextual factors. A students’ approach to learning is shaped by many factors (Biggs, 1987; Rowe, 2002; Tait, & Entwistle, 1996; Zeefers, 2002). In our case, students were enrolled in a college course in which lecturing was the primary teaching strategy and assessment of learning was based on students’ ability to solve traditional organic chemistry problems. In this
context, our results suggest that the majority of the study groups adopted a strategic approach to studying by using instructor-provided problems, working from old exams, and minimizing effort by deferring to the expertise of more knowledgeable others. In this context, co-construction was a more time-consuming, unnecessary method of interacting, and was most likely to be used only in cases where direct sources of information were absent.

Given this information, we suggest that college instructors in chemistry and other science courses reconsider many of the instructional and assessment practices that are in place. Our results indicate that students’ methods of studying were highly influenced by the nature of the course for which they were studying. First, the context of the class is likely to affect students’ interactions within their study groups. Students who engage in group work within an active learning classroom are more likely to become skilled at articulating scientific arguments and co-constructing knowledge within their groups (Richmond & Striley, 1996; Sokolove & Marbach-Ad, 1999). A learning environment that reinforces student-centered learning and encourages exploration of concepts in deeper and unfamiliar ways may advance students from a strategic to a deeper approach to learning (Trigwell, Prosser & Waterhouse, 1999). Through a collaborative process, students can be encouraged to analyze, discuss, and debate ideas, which are all examples of higher cognitive strategies (Tang, 1993).

Additionally, we found that a majority of groups studied by working through problems that were either suggested or provided by their instructor. By providing their students with these types of problems, instructors have a straightforward method of
influencing the content from which students study. Instructors need to more carefully and critically approach the task of developing or suggesting these types of study guides. If students are not rewarded for taking the extra effort to discuss a concept by working collaboratively, they are unlikely to do so (Volet et al., 2009a). Because students are highly influenced by suggestions that instructors make, we additionally suggest that further assistance be given to students in the form of recommendations about proper study techniques. Finally, assessment resources and tools should be enriched and diversified to include questions that require students to think about concepts in new ways (Gibbs & Simpson, 2004-05; Thomas, Bol, & Warkentin, 1991). In order to encourage study groups to interact and discuss content in the most productive manner, it is important for instructors to create opportunities for more generative forms of collaboration and to create practice problems and exams that reflect higher levels of content processing. Appendix C outlines some example problems that could be used to target these different levels of content processing.
CHAPTER 3: STUDENT REASONING ABOUT ORGANIC CHEMISTRY CONCEPTS

Framework

Much of the research conducted on reasoning in chemistry has focused on problem-solving approaches of students working on quantitative problems (Bodner & Herron, 2002). Studies regarding chemical problem-solving approaches have outlined the necessary steps or processes involved in problem-solving (Bodner & McMillon, 1986), discussed the characteristics of good problem-solvers (Tingle & Goode, 1990; Bodner & Domin, 2000), and outlined the problem-solving strategies for students within the chemistry discipline (Chandrasegaran, Treagust, Waldrip, & Chandrasegaran, 2009). In general, chemistry students tend to be overly dependent on algorithmic problem-solving strategies. Most often, when solving traditional problems, students have minimal consideration for conceptual understanding, with a predilection to focus on algorithmic approaches. Whenever possible, students apply or create algorithms even for those problems which might be intended to elicit abstract thought processes (Nakhleh & Mitchell, 1993).

With respect to organic chemistry, research studies have investigated some of the qualitative reasoning approaches that students use. This is a course that requires far more qualitative decision-making than general chemistry, although students are still apt to rely on systematic reasoning processes. When drawing mechanistic pathways, for example, students often rely on structural cues to determine the differences between reactants and
products and then simply “connect-the-dots” when building a mechanism (Bhattacharyya & Bodner, 2005). This algorithmic approach allows students to propose a mechanistic pathway without consideration of the sometimes competing factors related to reactivity. Other studies of student reasoning in organic chemistry have examined domain-specific responses to qualitative reasoning tasks such as interpretation of $^1$H NMR spectra (Cartrette & Bodner, 2010), approaches to mechanistic tasks (Strickland, Kraft, & Bhattacharyya, 2010; Bhattacharyya & Bodner, 2005; Ferguson & Bodner, 2008), or synthesis problems (Tsaparlis & Angelopoulos, 2000).

The majority of such studies have focused on students working on assigned tasks within the confines of an interview protocol. Lacking among this type of research are studies which investigate student reasoning pertaining to student-selected tasks. Additionally, students who study with group members are expected to demonstrate different types of justification for their reasoning choices. For example, individuals who are challenged by questions from peer students are likely to change their types of explanations as a result (Roscoe & Chi, 2004, 2007). Students also offer targeted explanations pertaining to the specific area of difficulty that others in their group might be facing (Vedder, 1985). In this way, students build explanations for others in their group that reflect the types of reasoning that they value. For this reason, additional research investigating chemical thinking among student peers in study groups would add to our understanding of reasoning processes that are used and valued by students in organic chemistry. An understanding of these methods of reasoning is important when targeting instruction to chemistry students. In particular, when and how students apply
different types of reasoning may indicate their ability to articulate or wrestle with scientific concepts (Justi & Gilbert, 2002). By better understanding the process of reasoning that students employ, as well as the relevant features that affect their reasoning, we are one step closer to influencing the ways in which students discuss, think about, and articulate chemistry concepts within their study groups.

Individuals who are faced with a task may reason through it using a combination of different reasoning methods. Often, individuals will use both logical as well as intuitive or “common sense” reasoning in their thinking to come to a conclusion (Evans, 2004). When individuals reason about a subject, they do not necessarily make a conscious decision to employ one method of reasoning over the other, but several factors may combine to influence their use of one system of reasoning over the other. For example, the classroom environment, time constraints, or even biological factors may affect the type of reasoning that students employ (Masicampo & Baumeister, 2007; Patel, Groen & Norman, 1991). Additionally, the presence of incongruent information or unfamiliarity with a subject may influence an individual to spend a greater amount of effort analytically processing the information through a slow system of reasoning (Maheswaren & Chaiken, 1991). To this effect, individual differences in mastery of a subject, in addition to structural features of a course or prompt may affect the method of reasoning that individuals use.

Research pertaining to student reasoning in chemistry problem-solving activities has shown that students tend to use shortcut methods when reasoning about tasks. For example, students tend to use algorithms and heuristics or other shortcut strategies when
solving problems such as those which require classification (Stains & Talanquer, 2007) or ranking of chemical substances (Maeyer & Talanquer, 2010; McClary & Talanquer, 2010). When working on quantitative tasks, students tend to strongly rely on means-ends analysis strategies (Heyworth, 1999), and their problem solving ability is not necessarily correlated to a deep conceptual understanding (Nurrenbern & Pickering, 1987).

The specific methods of reasoning that chemistry students might use in their problem-solving approaches are varied, although a recent study examined three methods of reasoning that students used when solving novel mechanism tasks. The authors identified three major types of student reasoning, which are known as model-based reasoning (MBR), case-based reasoning (CBR), and rule-based reasoning (RBR) (Kraft, Strickland, & Bhattacharyya, 2010). For further clarification on how students within the organic chemistry course might be expected to utilize these different methods of reasoning, please see Appendix A.

Model-based reasoning is based on the construction of a mental model of an object or process and is based on implicit assumptions about the nature of things, prior knowledge and experiences, as well as perceptual and verbal cues about an entity or phenomenon (Nersessian, 2008). The creation of a student’s mental model is a process which combines their prior knowledge with information from explicitly taught chemical models. The development of a mental model is not a linear process as it often includes frequent revision, and this process is enhanced when students use their mental models to solve problem tasks or evaluate their ideas (Buckley & Boulter, 2000). By using model-
based reasoning to reason out loud with their group members, students thus have the opportunity to further develop their mental models.

Model-based reasoning uses the predictive and explanatory power of a model in order to make a decision (Gilbert, Boulter, & Rutherford, 1998). Scientific theories are themselves developed models that use words and mathematical relationships to represent information or map ideas (Giere, 1990). The field of chemistry in particular is shaped by many models that are used to describe and predict the nature of macroscopic and sub-microscopic properties of the world (Justi & Gilbert, 2002). As Bent described them, the models within chemistry are “metaphors of small, invisible, quantum mechanical things” (1984, pg 774). These models are of central importance to chemists as a means of representing and investigating qualitative aspects of matter (Erduran, 2001). Because models play such an important role in science, it follows that students of chemistry would also be expected to demonstrate an ability to reason with and draw inferences from models; however, research indicates that the nature of chemical models may sometimes pose difficulties for students. For example, multiple models are sometimes used within the field of chemistry to analyze chemical properties (e.g., Arrhenius vs. Brønsted-Lowry model of acids), and many students may fail to recognize the differences and range of application when generating synthetic mental models pertaining to these ideas (McClary & Talanquer, 2011).

Two of the common modes of representation for models in organic chemistry include the concrete mode (such as the ball and stick model of a molecule) and the verbal mode (spoken words) (Gilbert, et al., 1998). In both cases, they are based on qualitative
theoretical concepts (scientific models). Students may draw from physical representations of a compound in conjunction with conceptual models when reasoning and discussing chemistry content (Treagust, Chittleborough, & Mamiala, 2004). In any case, model-based reasoning can be useful in helping an individual to create explanations, yield novel relations, and improve overall understanding of science content (Gilbert, Boulter, & Rutherford, 2000; Halloun, 2007; Johnson-Laird, 2006).

Students may also reason by referring to a previous case that they are then able to adapt and apply to a current situation (Catrambone & Holyoak, 1989; Chi, Bassok, Lewis, Reimann & Glasen, 1989; Renkl, 1997; Van Lehn, 1998). Under these circumstances, a student would be using case-based reasoning to formulate the solution to a problem. By referring to known cases, individuals are able to use information that they are familiar with in order to solve a less familiar task. In this way, instances of similarity between a problem and a previous case provide the necessary overlap to reason through a novel situation. The recalled case acts by chunking relevant information together for easy retrieval. Rather than trying to piece together decontextualized pieces of information, a person can solve a problem as a complete unit by referring to an analogous case (Kolodner, 1993).

The process of case-based reasoning is dependent on two main aspects: the knowledge of past experiences, and the ability to apply these experiences (or cases) appropriately to a new situation. Memory, therefore, is an important part of case-retrieval, as a person must be able to remember from past experiences in order to have the necessary knowledge to draw upon (Leake, 1996). Within chemistry, case-based
reasoning is an important aspect of chemical thinking. A significant portion of our chemistry knowledge is organized through classification systems that categorize and order information about chemical substances based on their properties or processes. A classification system such as this can help chemists to make effective decisions about potential synthetic routes or methods of analysis (Kovac, 2002). Within organic chemistry, several computer programs have been developed which use case-retrieval as the basis for informing new decisions. These systems have shown that case-based reasoning is an effective method of reasoning when predicting reactions (Elrod, Maggiora, & Trenary, 1990) or proposing synthetic pathways (Gelernter, Rose, & Chen, 1990). In the same way, students can benefit from using analogous examples or cases to inform their decisions about new material (Kolodner, 1997).

A third method of reasoning that individuals may demonstrate is rule-based reasoning. In rule-based reasoning, students rely on a rule or a set of rules in order to discuss a topic (Kolodner, 1993). In doing so, students may use deductive reasoning to come to a conclusion (Chater & Oaksford, 2004; Wagman, 2003), or they may follow a rule-based procedure in order to reach a solution (Battista, 1999). Rules can be linked together in order to create a methodology for solving a problem or understanding a topic. By following a set of rules (or an algorithm), students can automate the steps necessary to solve a problem (Bodner, 1987). Often, these rules can serve as heuristics to more easily draw inferences and make quick predictions and decisions. This type of reasoning can be efficient in generating answers with low cognitive effort and processing time.
Much of the theoretical and practical knowledge in chemistry is represented in the form of rules (Kovac, 2002). General properties of substances are captured in rules such as “like dissolves like” or from periodic trends of atoms. Similarly, rules provide explanations for observed patterns: for example “Le Chatelier’s Principle” or “Zaitsev’s Rule.” These different rules are useful in the analysis and prediction of chemical structures and reactivity.

**Methodology**

*Goals and Research Questions*

The context of a study group provides a venue for witnessing spontaneous explanations and justifications, as students make visible their reasoning to others in their group. Because students predominantly study in self-initiated study groups by explaining concepts to one another (Hendry, Hyde & Davy, 2005), they are likely to verbalize these methods of analysis to one another. As the students interact with their classmates, they share their thought processes and reasoning behind decisions that they make. When students choose to reason about chemistry in a particular way, they demonstrate their implicit decision to value one method of reasoning over another in a given context. Therefore, the central goal of this study was to investigate the domain-specific types of chemical reasoning that students in self-initiated study groups used to communicate their understanding of organic chemistry content. In particular, our investigation was guided by the following research questions:

— What major types of reasoning approaches do students apply while reviewing organic chemistry content in self-initiated study groups?
— How does the nature of the questions and problems discussed in the study groups, as well as the types of interactions among group members, affect reasoning approaches?

— What levels of content processing are most frequently associated with the different types of reasoning observed in the study groups?

These research questions were used to guide the analysis of the data collected according to the methodology described in more detail in Chapter 2 and Appendix B.

Data Analysis

Audio recordings from each of the study group sessions were transcribed and analyzed in order to identify instances where students used different methods of reasoning. The transcriptions were first examined in order to identify episodes in which students were on-topic and discussing chemistry content. Segments where students were off-task or discussing non-content related aspects of their course were not used in this study. Codes were developed based on results from prior studies regarding types of chemistry problems (Davila & Talanquer, 2010) and reasoning in chemistry (Kraft et al., 2010). These coding categories addressed both the types of content focus that guided group work (e.g., reaction, mechanism) as well as the types of reasoning (e.g., model-based reasoning) that were reflective of study groups. As coding was implemented, new categories were created to address additional type of content focus or methods of reasoning (e.g., symbol-based reasoning). Transcriptions were segmented at the episodic level, so that for every shift in the type of reasoning, a different code would be assigned.
Additionally, we used the coding system described in the previous chapter (regarding student interactions and levels of content processing) to complement the analysis of student reasoning in this study. For additional information regarding either student reasoning in first semester organic chemistry or for further delineation of each type of coding, see Appendix A and B, respectively.

Once the coding system was proposed and agreed upon, the first researcher applied it to the analysis of one of the transcripts. A second researcher then reviewed the decisions regarding code application and segmentation, and further discussion helped to refine the codes. Both researchers individually analyzed transcriptions and compared their results until agreement reached 90%. Once this level of agreement was reached, the first researcher then applied the codes to the remaining transcriptions.

In order to compare between study sessions, the length of an episode was determined by counting the number of words spoken during that segment. In some instances, conversations between students would involve long pauses. At the same time, other sessions included students who would rapidly respond to one another, and sometimes overlapping conversations ensued. Keeping track of the number of words rather than a span of time allowed us to better capture the comparative length of different episodes. The relative frequency of different codes was determined by finding the percentage of words that corresponded to each code within the different study sessions and then averaging these values.
Results

The results section will be organized according to the research questions stated above. First, we will describe the reasoning processes observed for students discussing organic chemistry content within their study groups. Then we will describe how students’ reasoning approaches were affected by both the nature of the problems from which they worked, and the interactions of the group members. Finally, we will discuss the levels of content processing reflective of each type of reasoning.

Reasoning Processes

Our analysis indicated that students reasoned using four different reasoning processes when discussing organic chemistry content within their study groups. These methods of reasoning are described in some detail below. Three of them, model-based reasoning, case-based reasoning, and rule-based reasoning, can be thought of as instances of domain-specific cognition that result from domain-general processes operating on chemical concepts and ideas. The fourth one, symbol-based reasoning, can be characterized as a domain-specific strategy involving the manipulation of chemical symbology. It is important to point out that our goal during this part of the analysis was to typify student reasoning and not to evaluate the accuracy or quality of their thinking.

During instances of model-based reasoning (MBR), students used a model (generally either a concrete or theoretical model) to defend or explain a chemistry concept. At times, students created explanations using general chemical principles, although students would frequently work from less-developed mental models during their discussion. On average, each study session used model-based reasoning during 8.53% of
their total number of words (SD 12.3%), making it the least-commonly used method of reasoning between students. This is demonstrated in Table 3.1 which indicates the percentage of content-related words that correspond to each method of reasoning.

When working from case-based reasoning (CBR), students adapted known cases to fit a current problem. In general, the cases to which students referred were specific to the given circumstances (as opposed to a model, which could be applied in several different circumstances). On average, 26.1% (SD 27.4%) of group discussion utilized this method of reasoning (see Table 3.1).

Rule-based reasoning (RBR) was used the most frequently, at a rate of 56.7% (SD 32.3%). Under these circumstances, students cited rules when solving a problem. They would often discuss how to interpret a rule or decide under what circumstances it might be most appropriate to apply a rule. On the other hand, students would often pair multiple rules together or work from an algorithm in order to solve a problem.

A fourth type of reasoning that we identified was symbol-based reasoning (SBR). When the students used this method of reasoning, they did not appear to view the chemical structures as anything more than symbols. There was no indication that the students saw these symbols as representing a chemically-relevant structure or process within their discussion of the material. It appeared instead as though they simply manipulated the symbols on the paper in order to solve a problem or answer a question (Bhattacharyya & Bodner, 2005). On average, SBR corresponded to 8.66% (SD 9.85) of all the groups’ talk.
Table 3.1. Percentage of words corresponding to each method of reasoning, and relative to each study session that was observed, where SBR is symbol-based reasoning, RBR is rule-based reasoning, CBR is case-based reasoning, and MBR is model-based reasoning

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<th>% RBR</th>
<th>% CBR</th>
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<td></td>
<td>76.5</td>
<td>42.5</td>
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<td></td>
<td>58.6</td>
<td>6.99</td>
<td>74.0</td>
<td>2.25</td>
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</table>

**Influential Factors**

Depending on several factors, students relayed information to each other through the use of the four different types of reasoning (MBR, CBR, RBR, or SBR). The application of these types of reasoning depended on several contextual features. We investigated how group reasoning was affected by the exam for which students were studying, the subject matter that students were discussing, as well as the interactions among group members. We sought to characterize these factors in order to understand how they influenced the nature of student reasoning. The following sections discuss how group content focus as well as the interactions among group members affected (or failed to affect) student reasoning.

**Content Focus**

One of the most influential factors that affected how students reasoned was the subject matter that they discussed. Within any given problem, students might have addressed one of many different aspects of content inherent to that task, affecting as a
result their method of reasoning. For example, if a group tried to predict a mechanistic pathway, they might have focused on the representational meaning of the arrow-pushing formalism. Another group might have focused on the reactivity of a starting compound in order to understand the resulting mechanism. Both of these groups would, as a result, have used different methods of reasoning to discuss the same problem. Because students focused on different aspects of the same task, we kept track of the content focus that students discussed. Specifically, we determined that students would generally focus on five different aspects related to organic chemistry:

— **Representation**: Students tried to understand how to interpret or use a chemical representation (e.g., draw a Lewis structure or interpret a Fischer projection)

— **Structure**: Students discussed aspects related to the structural features of a compound (e.g., determine the formal charge on an atom, or determine the stereochemical relationship between two structures)

— **Reaction**: Students discussed the transformation of compounds according to a chemical reaction

— **Reactivity**: Students analyzed the likelihood of chemical substances reacting under certain conditions

— **Mechanism**: Students discussed mechanistic pathways that might account for structural transformations within a reaction

Students would focus on these five features when discussing chemistry content, or they would sometimes focus on a combination of these aspects. Overall, a correlation existed between the content focus of a group and the method of reasoning that came as a
result (Table 3.2 or Figure D.6). This was found by calculating the percentage of words pertaining to each set of codes within all of the study sessions and then taking an average of these values. From this analysis, we see that when students discussed representational or structural features, they tended to use rule-based reasoning. Similarly, as students focused on specific reactions, they would use case-based reasoning by recalling a specific reaction as a given case.

Table 3.2. Ways in which study groups discussed organic chemistry with respect to five different content focuses

<table>
<thead>
<tr>
<th>Problem Focus</th>
<th>SBR</th>
<th>RBR</th>
<th>CBR</th>
<th>MBR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg % (SD)</td>
<td>Avg % (SD)</td>
<td>Avg % (SD)</td>
<td>Avg % (SD)</td>
</tr>
<tr>
<td>Representation</td>
<td>15.1 (28.1)</td>
<td>76.6 (28.5)</td>
<td>4.88 (8.38)</td>
<td>3.47 (10.9)</td>
</tr>
<tr>
<td>Structure</td>
<td>10.4 (15.1)</td>
<td>58.5 (32.9)</td>
<td>17.2 (27.8)</td>
<td>13.9 (21.4)</td>
</tr>
<tr>
<td>Reaction</td>
<td>2.29 (4.72)</td>
<td>8.01 (13.3)</td>
<td>89.5 (14.2)</td>
<td>0.183 (0.775)</td>
</tr>
<tr>
<td>Reactivity</td>
<td>10.4 (23.0)</td>
<td>38.3 (32.5)</td>
<td>19.9 (20.9)</td>
<td>31.5 (33.1)</td>
</tr>
<tr>
<td>Mechanism</td>
<td>32.8 (36.7)</td>
<td>12.8 (22.6)</td>
<td>43.8 (36.3)</td>
<td>10.7 (24.8)</td>
</tr>
</tbody>
</table>

Both representation and structure were most highly correlated with rule-based reasoning (76.6% and 58.5% of discussion, respectively). The students in our research study spent a significant portion of their study sessions using rules as the basis for their understanding of different chemical features. For example, in the excerpt below, two students used a combination of rules in order to determine the name of a given structure (Figure 3.1).
Name the following compound:

\[
\begin{align*}
\text{CH}_3 \\
\text{H}_2\text{C} - \text{C} - \text{CH}_3 \\
\text{CH}_2 \\
\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3
\end{align*}
\]

Figure 3.1. An instructor-provided nomenclature problem.

O: Now, because there’s two methyls, I would say 2 comma 8 dimethyl. Neopentyl nonane. Because the ane goes last.
F: Yeah. And why’d you put dimethylneopentyl instead of neopentylidimethyl?
O: Because M comes before N.
F: Okay.
O: Okay. And even though there’s no number it would be neopentyl dash nonane? Like, I mean because nonane is a chain, it’s not like there’s a location. But there’s a dash.
F: No dash.
O: There’s no dash.
F: Because it’s dash between different things and commas between likes.
O: Oh right, he said that. Where did I write that? Maybe I didn’t write it. Can you say that again? That was good.
F: Dashes between different and commas between likes.

The discussion between these two students focused on a number of discrete rules that they had memorized. For example, they mentioned a rule for alphabetization of components in the name. Student “F” also explained a rule for dashes that he remembered: “dashes between different and commas between likes.” As such, their basis for determining the name of the structure of interest came primarily through rule-based reasoning.

Within the organic chemistry course, representational and structural features were often discussed or manipulated through a series of rules. In the previous example, the representation of a structure (its name) was derived through a series of rules. Similarly,
when students described the hybridization around an atom or calculated the degrees of unsaturation in a compound (issues of structure), they frequently applied rules or formulas in order to understand a structural feature.

There were occasions when the students did not automatically know what rules they should apply in order to solve a problem. Particularly when discussing different types of representations, students would need to look for information pertaining to the words or symbols used to represent a substance. In these cases, students would seek to define a term or understand a rule. For example, students might have sought to understand the definition of a term (such as neopentyl) when discussing nomenclature. Later in the semester, they might have sought to find a rule to differentiate between strong and weak nucleophiles. A significant portion of discussion related to RBR was spent determining the proper rule that should be employed in a given situation.

Student discussion related to chemical reactions most commonly resulted in case-based reasoning (89.5% of discussion, see Table 3.2). Students frequently reproduced the product of a reaction from memory by categorizing a reaction as a specific instance of a more general case. In the example below, the students worked together to predict the product that would form when an alkene reacted with Br₂ in THF (Figure 3.2). Their response to this problem demonstrates what case-based reasoning looked like.

![Figure 3.2](image)

Figure 3.2. A student-created problem which required the study group to find the product of a reaction.
J: What is that called? What is that reaction called?
A: Halogenation.
J: So you’re going to have two halogens added on.
L: Okay, so. Because we’re going to do, because we’re doing anti, they’re going to go like this. Now, this is where the double bond is, so we’re going to do a Br here and a Br here.
J: Keep in mind what the intermediates look like. It’s the triangle with the Br.

Because the students were able to recognize the reaction as a case of the halogenation reaction, they were able to recall what the product and intermediate would look like. The students recalled a piece of memorized information and were able to use it to solve a problem, because it matched a more general case that they were familiar with.

Another instance where students discussed reactions using case-based reasoning was when they considered different synthetic pathways. In the following example, students worked on a synthesis problem by considering reactions as specific cases. In this example, they did not reproduce a synthetic pathway from memory, but rather, approached the problem by determining the differences in structure between product and reactant in order to find the reagents that would produce this change (Figure 3.3). They utilized case-based reasoning by referring to reactions as specific cases.

![Figure 3.3](image_url)

Figure 3.3. An instructor-provided problem which required the students to propose a synthetic pathway.
N: Okay, so what I’m assuming he’s doing is doing a 1,2 methyl shift. Right there. Or add a bromine there, so a Br$_2$ with light, which is a reaction that we don’t ever do. And then doing the $S_N2$ you get the CN.

T: HBr would be, or H$_2$O$_2$, so it would do anti markovnikov. So then it would have added there, but then, yeah, I don’t know what would have made it switch beyond that.

N: Or hydroboration. So that would make an OH right there. Or wait. Yeah. An OH right there. And then keeping the same stereochemistry. Or these would be opposite.

These students looked at structural differences between the reactant and product in order to brainstorm different reactions that could account for these structural differences. This was case-based reasoning, because the students viewed the types of reactions as specific cases that could transform functional groups.

When discussing issues of reactivity, students were most likely to use either rule-based reasoning (38.3%) or model-based reasoning (31.5%). If using rule-based reasoning, a student may have cited a rule in order to determine the likelihood of a reaction to progress in a particular way or to determine the likelihood of a given product to form. For example, a student might cite the Zaitsev rule as reason for the location of the most stable double bond. Another student might proclaim that halides always make good leaving groups, making a particular substrate more susceptible to nucleophilic substitution than another.

Students who used model-based reasoning to discuss issues of reactivity often elaborated within their discussion to better comprehend the differences between reactivity of different substrates. In the example below, the group’s discussion focused on an explanation for why only certain carbocations reacted through the $S_N1$ mechanism.

E: The bond between two carbons is typically equally shared. So looking at this tertiary carbocation. Typically these bonds between these carbons
are the same, because they’re equally shared, they’re the same element, so they’re indistinguishable. So, they both share the electrons perfectly, evenly. But when we put a positive charge on one of those carbons, what can happen is, is called the inductive effect. So that can pull in a little bit of the electron density that it would typically share. It says, I’m a selfish carbon, and it will keep it. This won’t work with a proton, because hydrogen is just that little bit more electronegative and it won’t share, so therefore you have less stabilization on the primary carbocation. So that’s not stable. These guys won’t help. So primary ones aren’t going to form. So we know for our S_N1 reaction that we need to have tertiary, secondary carbocations.

This student used the principles behind the inductive effect in order to explain the difference in reactivity for different substrates in the S_N1 reaction. During this particular explanation, the student misapplied the inductive effect rather than using the accepted theory of hyperconjugation to correctly explain carbocation reactivity. Nevertheless, this student used a model (regardless of its misapplication) to create an explanation of reactivity in the S_N1 mechanism. In this way, MBR was frequently used to describe or explain issues related to the reactivity of chemical substances.

Finally, the content focus of reaction mechanisms was commonly discussed through either the use of case-based reasoning (32.8%) or symbol-based reasoning (43.8%). Students who recalled a particular reaction type were sometimes able to reproduce entire mechanisms completely from memory once they knew the reaction-type to which it corresponded. On the other hand, students who discussed mechanisms by using symbol-based reasoning often did so by using a method of analysis called “connect-the-dots” (Bhattacharyya & Bodner, 2005). Using this approach, students recognized structural differences between the reactant and product in order to map the arrow-pushing formalism. In both case-based reasoning and symbol-based reasoning
involving mechanistic pathways, there was little discussion related to matters of chemical
significance such as reactivity, stability of intermediates, or plausibility of mechanistic
pathways. This meant that a common way for groups to discuss mechanisms was to do
so without a chemical explanation of the reasoning behind the mechanistic steps.

As an example, in the following excerpt, two students worked on a problem
where one reactant formed a mixture of different products when reacted with HBr (Figure
3.4). The students knew what the structure of both the reactant and products looked like,
and they were asked to provide a plausible mechanism to account for the different
products. They used a symbol-based reasoning approach to solve this problem.

Figure 3.4. An instructor-provided problem requiring students to propose a mechanism
to account for several different products.

T: It would be something like that. And then your intermediates are going
to be . . . here. And then Br minus. That’s what the intermediates are.
That bond is going to break, it’s going to go here. It will just bond like
anywhere on this? That’s what I think.
A: Well, this is the final product though. So the bromine doesn’t leave.
T: Yeah. Like, I’m leaving that one below.
A: So just.
T: And when you have the intermediates, you don’t. These two electrons
will go, this bond will break, and it will go to hydrogen, and this Br will
form a bond down here. So let’s look and see what we have (looks at the
answer) Oh. Ohh, okay. Yeah. We have to put a positive charge over
here, because that bond is breaking.
In this excerpt, the students did not use chemically-relevant explanations to describe the decisions they were making about how to draw the mechanism. They appeared to simply be making bonds, drawing arrows, and pushing electrons as a means to account for structural differences between the reactant and products. Student A’s comment that “This is the final product . . . so bromine doesn’t leave” indicates that she looked to the final products to determine what the mechanism would look like. This excerpt is indicative of the way in which students used SBR to discuss a mechanism.

Overall, students’ methods of reasoning were highly dependent on the subject matter that was discussed. As there was significant overlap between these two areas, it is relevant to consider the conditions under which different content areas were discussed. In general, the content on which students focused tended to mirror the course content that was covered in the lecture portion of the organic chemistry course. Although there was not a set curriculum for all organic chemistry courses, most instructors tended to follow a similar progression. The first half of the semester focused heavily on representational or structural issues and the second half focused primarily on reaction types (see Table 2.1).

It follows, therefore, that students spent the greatest proportion of their words discussing representational and structural features in preparation for the first two exams of the semester. Additionally, there was minimal discussion of reactivity, mechanisms, or reactions during the first two exams, although this increased in preparation for the third exam and beyond. As students focused on different content within the organic chemistry semester, the types of reasoning in which they engaged changed as well. Table 3.3 shows the types of reasoning that students used to explain concepts to each other,
specific to each exam (also shown in Figure D.7). As is indicated in this table, certain types of reasoning changed noticeably throughout the course of the semester, paralleling the changes to course content. Participation through rule-based reasoning was the most common method of reasoning overall, although this decreased significantly across the course of the semester. Conversely, case-based reasoning increased considerably as the semester progressed. The level of participation in the category of symbol-based and model-based reasoning remained relatively constant throughout the semester (Table 3.3).

Table 3.3. Types of reasoning that students used in preparation for each exam, reported as a percentage of the words that students spoke in each given study session

<table>
<thead>
<tr>
<th>Exam</th>
<th>SBR Avg % (SD)</th>
<th>RBR Avg % (SD)</th>
<th>CBR Avg % (SD)</th>
<th>MBR Avg % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exam 1</td>
<td>5.31 (7.91)</td>
<td>81.7 (15.3)</td>
<td>6.80 (12.9)</td>
<td>6.17 (8.9)</td>
</tr>
<tr>
<td>Exam 2</td>
<td>10.4 (8.44)</td>
<td>68.4 (20.6)</td>
<td>14.2 (11.9)</td>
<td>6.14 (7.85)</td>
</tr>
<tr>
<td>Exam 3</td>
<td>12.8 (15.4)</td>
<td>21.4 (23.6)</td>
<td>58.1 (26.2)</td>
<td>7.62 (5.55)</td>
</tr>
<tr>
<td>Exam 4</td>
<td>10.4 (9.40)</td>
<td>39.4 (26.3)</td>
<td>33.7 (24.4)</td>
<td>15.7 (25.3)</td>
</tr>
</tbody>
</table>

Another factor influencing the content focus (and as a result the type of student reasoning) that was studied was the type of problem from which students worked. The most common way for groups to study was to work from problems that were provided by their instructor (such as a practice exam) or those that were suggested by their instructor (for example, problems in the text book). These problems became the focus of group discussion, and they often determined the content that was discussed between group members, thereby influencing the type of reasoning that students used as a result.
Certain problems from which students worked elicited very specific types of content and methods of reasoning. For instance, problems which required students to describe the relationship between two molecules (for example, determine the type of stereoisomer) elicited discussion of which 80.4% was correlated to rule-based reasoning (Table 3.4). This type of problem promoted student discussion that was focused on the subjects of representation or structure, and as a result, students used RBR most commonly to come up with a solution. There were many other problems such as these, where students’ methods for discussing the solutions were almost universal.

Other problems elicited more varied responses. For example, when students were asked to propose a mechanism to explain a given product, there were several approaches that groups would take. They might have focused on the representational meaning of the arrow-pushing formalism (resulting in a rule-based approach). Other groups might have focused on the reactivity of a starting compound in order to understand the resulting mechanism (more likely to result in model-based reasoning), and still other groups might have referred to known reactions for which they knew the mechanisms (case-based reasoning). A significant portion of the students responded to this type of problem through each of the four identified methods of reasoning (Table 3.4). Other types of problems also appeared to allow for several pathways of problem-solving, and we observed that students working on these tasks would take varied approaches and would not confine themselves to using just one method of reasoning throughout the discussion of a problem.
Table 3.4. Eight of the most common types of instructor-provided problems from which students worked, and the type of reasoning which corresponded to each problem

<table>
<thead>
<tr>
<th>Common Problem</th>
<th>SBR Avg % (SD)</th>
<th>RBR Avg % (SD)</th>
<th>CBR Avg % (SD)</th>
<th>MBR Avg % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predict Product (n = 53)</td>
<td>16.3 (29.9)</td>
<td>12.8 (26.0)</td>
<td>67.6 (40.3)</td>
<td>3.36 (10.4)</td>
</tr>
<tr>
<td>Name Compound (n = 33)</td>
<td>4.20 (18.5)</td>
<td>90.1 (25.7)</td>
<td>5.76 (19.3)</td>
<td>0.00 (0.00)</td>
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<tr>
<td>Identify Type of Isomer (n = 21)</td>
<td>0.569 (1.95)</td>
<td>80.4 (40.0)</td>
<td>19.1 (40.2)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Translate Representation (n = 12)</td>
<td>11.5 (2.31)</td>
<td>72.9 (38.1)</td>
<td>9.18 (28.8)</td>
<td>6.41 (22.2)</td>
</tr>
<tr>
<td>Propose Mechanism (n = 8)</td>
<td>40.7 (29.9)</td>
<td>20.9 (27.6)</td>
<td>22.7 (21.2)</td>
<td>15.8 (35.2)</td>
</tr>
<tr>
<td>Propose Synthetic Pathway (n = 7)</td>
<td>4.00 (10.6)</td>
<td>14.2 (15.7)</td>
<td>81.8 (22.2)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>Predict Reactant (n = 5)</td>
<td>1.03 (10.6)</td>
<td>54.1 (40.4)</td>
<td>40.0 (40.6)</td>
<td>4.95 (7.21)</td>
</tr>
<tr>
<td>From NMR Predict Structure (n = 5)</td>
<td>8.76 (10.6)</td>
<td>84.0 (16.8)</td>
<td>7.26 (16.2)</td>
<td>0.00 (0.00)</td>
</tr>
</tbody>
</table>

Social Regulation

The content focus explained much of the variability in types of reasoning that students used to discuss course material, although we intended to examine the effect of group interactions on student reasoning as well. Chapter 2 described in greater detail the types of student interactions that were observed, but we will summarize here the three representative methods of interactions. Within the co-construction interaction, two or more students collaboratively contributed to a group understanding of some concept. Within this interaction, students participated in an equivalent manner by suggesting ideas,
brainstorming together, or arguing content. Within the *tutoring* interaction, two different roles were present. Students either requested information from others in the group or responded by answering questions and creating explanations. When tutoring, it was the student who posed questions who determined what content was covered. Finally, the *teaching* interaction occurred when one student provided information to others in the group. This person determined what content to discuss, while others were more passive in their participation.

In general, we found that student interactions resulted in fairly consistent quantities of each type of reasoning (Table 3.5 or Figure D.8). That is to say that students on the whole did not reason in an appreciably different manner as a result of engaging in a different type of interaction. The only significant difference (p<0.02) was with respect to model-based reasoning. Students were more likely to apply model-based reasoning when they were tutoring or teaching rather than co-constructing information.

<table>
<thead>
<tr>
<th>Social Regulation</th>
<th>SBR Avg % (SD)</th>
<th>RBR Avg % (SD)</th>
<th>CBR Avg % (SD)</th>
<th>MBR Avg % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching</td>
<td>6.49 (11.1)</td>
<td>58.0 (35.2)</td>
<td>26.1 (29.5)</td>
<td>9.45 (16.4)</td>
</tr>
<tr>
<td>Tutoring</td>
<td>9.87 (13.9)</td>
<td>55.5 (34.6)</td>
<td>24.8 (28.3)</td>
<td>9.81 (13.3)</td>
</tr>
<tr>
<td>Co-constructing</td>
<td>8.17 (12.9)</td>
<td>61.0 (34.9)</td>
<td>27.0 (31.9)</td>
<td>4.40 (10.7)</td>
</tr>
</tbody>
</table>

Groups that used model-based reasoning to discuss chemistry content were likely to do so under specific conditions. Within both the teaching and tutoring interactions, there was a student who took the role of providing information to the rest of his or her
group members; we found that the students who used model-based reasoning generally engaged in this role of explaining concepts to other students. In the instances where groups used MBR while tutoring each other, there was one individual present who was able to answer a question and use a model to explain his or her reasoning. Similarly, within the teaching interaction, there was generally one individual who did most of the speaking and through their teaching demonstrated MBR. In the following excerpt, a group engaged in a teaching interaction while discussing chemistry content through model-based reasoning (Figure 3.5).

![Chemical Reaction Diagram](image)

Figure 3.5. A student-created prompt that elicited a conversation regarding the reactivity of substrates in $S_N_1$ reactions

**R:** So this bond between the carbon and the chlorine, is polar. What could happen?

**B:** It might fall apart.

**R:** It might fall apart. So if it does fall apart, we’re going to have a carbon, which would still have three methyl groups on it. And because it’s now missing that, because the chlorine takes the electrons with it when it goes, you get a carbocation intermediate. Still surrounded by that ethanols. This might stay as a carbocation for a little while. However, all around it are these ethanols. And the ethanols have lone pairs on them. (pause) Those lone pairs are pairs of electrons, so they have a negative charge. And this has a positive charge on this carbon. What do you think they will do?

**B:** They’ll probably try to attack the molecule and try to attach to it.

**R:** Right. Nucleophiles attack the positive charge. So we draw an arrow from the lone pair to the carbocation.

In this example, “R” described to her study group how the reactivity and mechanism of a substitution reaction were related to electrostatic interactions between the
substrate and the nucleophile. The other group members did not speak extensively and only offered suggestions when prompted to do so. Without this individual’s presence, it is questionable whether or not the group would have used MBR to describe the chemistry content.

Additionally, we saw that the individual “R” was not necessarily demonstrating the thought process that she might use to make decisions about substitution reactions. Rather, she was trying to help the other study group members to build a more conceptual understanding of the explanation behind certain trends in reactivity. This was a common attribute of study groups that used MBR. Students who taught or tutored their group members would frequently use MBR as an explanatory tool. These students used MBR to explain the theory behind a given concept rather than use it to demonstrate their thinking while actively coming up with a solution to a problem. In other words, students who were teaching others may or may not have been using model-based reasoning as a personal means to come up with a solution to a problem for themselves, but they would use it when explaining their solution or a concept to other students. Thus, MBR was most commonly demonstrated as a way to generate conceptual explanations for others in a group.

Frequently, when MBR was used within study groups, it came as a result of a student who appeared to be knowledgeable and well prepared in the subject area of organic chemistry. In the example above, the individual, “R,” who took on the teaching role, was in fact a teaching assistant for some of the students in the study group. She was asked to be present for one of the group’s study sessions, and when she came, took
control over the content that was being discussed by the group. This TA, who was a graduate student in the Chemistry and Biochemistry department, had more background knowledge from which she could draw to explain organic chemistry using MBR. Within this particular session, the students spent the highest percentage of words (67%) of any observed study group participating in model-based reasoning (Table 3.1), and this came almost exclusively as a result of the TA who was leading the discussion. This study session exemplifies what we saw in other cases, where the majority of model-based reasoning came as a result of a knowledgeable member of the study group who took the lead in teaching or tutoring the rest of the group members. It was far less common for several group members to participate in MBR jointly through the use of a co-construction interaction.

Student Content Processing and Methods of Reasoning

When students used different types of reasoning, they tended to discuss the material at different levels of content processing. Chapter 2 describes in some detail the levels of content processing that were characteristic of these self-formed study groups as they discussed organic chemistry material. A modified Bloom’s taxonomy was used to describe student thinking (Krathwohl, 2002) in order to hierarchically rank the levels of content processing from low (remember, understand, and apply) to high (analyze and create). In particular, the analysis of study group transcripts yielded the following main levels:
— Remember: Students retrieved relevant information from long-term memory and used it to, for example, define concepts, recall values, identify categories, or recognize processes in order to solve a problem or answer a question.

— Understand: Students tried to determine the meaning of concepts or ideas by, for example, interpreting chemical representations, comparing chemical processes, building inferences, and explaining ideas.

— Apply: Students used their knowledge to solve a problem following two main approaches:
  - Executing: carrying out a well-established set of procedures
  - Implementing: more freely applying learned principles without the use of an algorithm or set of rules to follow

— Analyze: Students broke down information into parts in order to detect how the different components related to one another. Multiple factors were considered in order to interpret a problem. At this level, we differentiated content-specific methods of analysis:
  - Connect-the-dots: Students created reaction mechanisms based on structural differences between reactants and products.
  - Mechanistic: Students created reaction mechanisms using chemical principles to propose a sequence of events.
  - Synthetic: Students compared structural differences between products and reactants to propose reaction conditions or synthetic pathways that would accommodate these differences.
Generic: Students used generic procedures to analyze chemical structures and processes.

— Create: Students put together information in order to generate an answer, for example inferring the structural formula of a chemical compound from different types of spectroscopic data.

In general, over 70% of observed content-related conversations corresponded to lower levels of content processing (remember, understand, and apply) regardless of student reasoning methods; however, the results indicate that the reasoning types of SBR, RBR, and CBR were more prone to induce lower levels of content processing (Table 3.6 or Figure D.9). In particular, symbol-based reasoning and case-based reasoning were frequently based on students’ recalling of specific examples or remembering types of substances or processes (remembering). Rule-based reasoning resulted in discussion pertaining to recalling rules or applying these rules, generally by executing an algorithm.

<table>
<thead>
<tr>
<th>Levels of Content Processing</th>
<th>SBR</th>
<th>RBR</th>
<th>CBR</th>
<th>MBR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Remember</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg % (SD)</td>
<td>52.3 (31.3)</td>
<td>35.1 (18.0)</td>
<td>62.6 (28.3)</td>
<td>3.16 (6.16)</td>
</tr>
<tr>
<td><strong>Understand</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg % (SD)</td>
<td>21.4 (27.3)</td>
<td>9.82 (13.1)</td>
<td>12.4 (22.8)</td>
<td>50.1 (41.1)</td>
</tr>
<tr>
<td><strong>Apply</strong></td>
<td>Executing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg % (SD)</td>
<td>4.45 (15.2)</td>
<td>28.1 (26.7)</td>
<td>3.35 (10.4)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td></td>
<td>Implementing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg % (SD)</td>
<td>9.36 (23.1)</td>
<td>10.1 (17.6)</td>
<td>11.6 (16.7)</td>
<td>19.8 (32.9)</td>
</tr>
</tbody>
</table>
Connect-the-dots  | 11.5 (27.1)  | 0.689 (3.96)  | 0.758 (2.84)  | 0.00 (0.00)  

**Analyze**  
Avg % (SD)  
Mechanistic  | 0.00 (0.00)  | 6.66 (19.0)  | 0.044 (0.222)  | 11.0 (28.9)  
Synthetic  | 0.00 (0.00)  | 0.00 (0.00)  | 5.13 (12.3)  | 0.00 (0.00)  
Generic  | 0.192 (0.922)  | 7.91 (15.9)  | 4.02 (9.13)  | 15.9 (30.7)  

**Create**  
Avg % (SD)  
0.725 (3.48)  | 1.59 (5.42)  | 0.00 (0.00)  | 0.00 (0.00)  

We saw that students spent a greater percentage of their words at the level of analysis when participating in model-based reasoning (26.9% of words), indicating that model-based reasoning resulted in higher levels of content processing than for other types of reasoning (Table 3.6). Students who engaged in model-based reasoning spent the greatest proportion of their words, however, at the level of understanding (50.1%). This corresponds to results reported earlier, which suggest that MBR was predominantly used by students as an explanatory tool. Students explained concepts to one another so that others in their group could have a conceptual understanding of the basis for their decisions.

**Discussion, Conclusions, and Implications**

Our analysis indicated that organic chemistry students in study groups used a variety of methods of reasoning when discussing course material. Their preferred method of reasoning correlated closely to the type of subject matter that was discussed, and as different course requirements were presented, groups altered their methods of
reasoning to fit the specific circumstances. Social regulation played a minimal role in influencing methods of reasoning that were used, while the level of content processing differed significantly depending on the type of reasoning exhibited by students. On the whole, study conversations generally elicited either rule-based reasoning or case-based reasoning.

Students’ use of model-based reasoning tended to coincide with the highest levels of content processing. This evidence suggests that MBR may be a successful method for students to use when discussing higher-level organic chemistry concepts. Prior research shows that MBR is the most successful strategy that students used to solve unfamiliar mechanistic tasks (Strickland, Kraft, & Bhattacharyya, 2010). This is supported by our results which show that the greatest level of mechanistic analysis was demonstrated as a result of MBR (Table 3.6). Mechanistic tasks, in particular, often require consideration of several competing factors. Through the use of model-based reasoning, students may be more likely to acknowledge these competing forces in order to predict a rational mechanistic pathway. Additionally, because students were more likely to engage in higher levels of cognitive thought while using model-based reasoning, they may be more likely to give deeper consideration to the nuances of each specific reaction.

Model-based reasoning was not, however, a common strategy for groups, and when it was used, it often came about as a result of a specific individual. Prior research suggests that chemistry students often have naïve mental models (Coll & Taylor, 2002; McClary & Talanquer, 2011), or that students’ ability to reason with models is limited (Grosslight, Unger, & Jay, 1991; Stephens, McRobbie, & Lucas, 1999). Students are
often unaware of the limitations or scope of models, and may need help in deciding which to apply (Harrison & Treagust, 2000; Buckley & Boulter, 2000; Flores-Camacho, Gallegos-Cazares, Garritz, & Garcia-Franco, 2007). In our study, model-based reasoning generally transpired when individuals taught or tutored their group members about material that they had already mastered for themselves. These individuals had enough content knowledge (and well-developed mental models) to explain the material to the rest of the group. This suggests that while certain students were able to inform their group members through MBR, not every student was able to (or willing to) communicate by using overarching chemical models when studying.

While it is possible that certain students may have been using a model to think about a subject while verbalizing their reasoning in some other way, the fact that most students failed to express MBR to their group members indicates that many did not see MBR to be a strategic reasoning strategy worth sharing with their group members. By noting the relative prevalence of students’ expressed methods of reasoning, we were able to see which types of reasoning were implicitly valued by students. Model-based reasoning was minimally used as a reasoning strategy, indicating that students were either unable to use this method of reasoning, or that they did not see the value in using MBR. Instructors might hope that their students would be able to cite scientific consensus models as justification for their choices. Evidence from our study suggests, however, that only a small proportion of students did so within their study groups.

Additionally, students appeared to use MBR as an explanatory tool, rather than a problem-solving tool. That is, even when MBR was applied, it was not commonly used
in order to work through a problem, but instead, to explain concepts to other students when further clarification was necessary. This suggests that for the most part, students were willing to work through problems without communicating scientific models to support their conclusions. So while RBR and CBR were strongly elicited throughout the course, this was not true for MBR. Students did not appear to be exposed to many circumstances for which they would be required to demonstrate model-based reasoning. Instructors who would like to help their students develop this type of reasoning may want to carefully consider what types of problems would elicit MBR, and how to encourage all students to be able to communicate using this strategy.

Within chemistry courses, students are sometimes taught about concepts or principles without being required to understand or participate in the modeling of that concept (Erduran, 2001). If instructors value their students’ ability to use MBR, they should make visible the weaknesses and explanatory powers of the chemical models that they use in the classroom (Buckley & Boulter, 2000), and should require their students to be involved in modeling activities themselves (Harrison & Treagust, 2000). This includes creating opportunities for students to provide justification for a reaction, or to evaluate the relative feasibility of a reaction mechanism.

Case-based reasoning was a common type of reasoning and was used most frequently during preparation for the third and fourth exams. Students primarily used CBR when they were talking about different reaction-types, although groups also discussed mechanisms through use of this type of reasoning. Students did not seem to have difficulty in categorizing reactions as specific cases pertaining to functional group
transformation. In fact, it is likely that this is a task that they were expected to perform (Lewis, 1999). They cited named reactions with ease and considered reactions which resulted in functional group transformations as cases that could be applied universally. This was a helpful skill for students to be able to develop and allowed students to easily predict products of a given reaction.

Generally, students applied case-based reasoning in an appropriate manner and to their advantage. However, it is interesting to note that many students thought of mechanisms as specific cases. This means that they were able to reproduce a mechanism by considering the type of reaction to which it corresponded without thinking about some of the chemically-relevant features that would explain the process. One student explained her perspective of this process to her group by describing organic chemistry as primarily an act in memorization:

*S:* You do one thing, and it could result in a ring opening up and having less strain, or it could result in a 1,2 hydride shift. It’s like, you just have to memorize what will happen in certain cases.

This student focused on memorizing specific cases of reactions or mechanisms without consideration of the underlying principles that could explain these transformations. From what we observed within each study group, this appears to be a fair appraisal of how many students studied. They tended to break down information into packets of data that could be easily categorized into specific cases. Groups saw reaction-types as falling into cases that could be memorized and then applied in new situations. They spent far less time discussing explanations to rationalize why reactions proceeded in the manner that they did. This allowed students to minimize the cognitive demand of a
problem and to discuss organic chemistry in an efficient manner. Unfortunately, for some students, such as the one quoted above, this efficiency resulted in a lack of conceptual understanding. While CBR was a beneficial strategy for study groups to use, there may be some instances in which students misapplied this reasoning strategy. Case-based reasoning allows a reasoner to reproduce a case without having to completely understand the domain under which it applies (Kolodner, 1993). This could pose a problem for students who apply cases in situations that are inappropriate without realizing their misapplication. Under certain circumstances, when it is necessary for students to have a theoretical basis for understanding a concept, model-based reasoning may be the appropriate strategy for students to work from instead.

In order to help students better understand when it would be appropriate to apply a case or not, instructors should discuss the conditions under which a case might be applicable. Students could also be asked to use a reaction that they are familiar with in order to predict the outcome of a similar reaction. Appendix C gives further examples of problems that might be used to elicit an appropriate case-based approach.

The most common type of reasoning that students used to discuss chemistry was rule-based reasoning, which was used in over half of student exchanges. Groups would frequently apply rules systematically in order to understand a representation or discuss structural features of a compound. Using RBR was a successful strategy for students to apply in the majority of cases, particularly when they were referencing the two subjects of representation or structure. As the semester progressed, and the course placed a
greater emphasis on reaction types, students altered their method of reasoning to focus more on case-based reasoning.

From this, we can ascertain that students altered their types of reasoning based on the subject matter that they were studying. The fact that students spent a majority of their time using RBR was likely due to the subject matter that was emphasized within the course. A majority of study groups worked from problem sets provided by their instructors. The fact that this elicited primarily rule-based reasoning as well as lower levels of content processing suggests that their instructors were emphasizing a specific aspect of chemistry that elicited this response. From past research, general chemistry problems at the end of text books have been found to be narrowly focused on specific tasks (Davila & Talanquer, 2010). It is possible that instructors in the organic chemistry course similarly focused on types of tasks that could be solved simply through the use of algorithmic application of rules. If instructors would like to see their students employ a variety of reasoning skills, they might carefully consider the types of tasks that they require their students to be able to perform.

Finally, within approximately 8.7% of all study group conversations, students neglected to provide relevant justification to other group members, preferring to simply manipulate chemical symbols upon a page. There was not any particular subject matter that was exclusively linked to students’ use of symbol-based reasoning, although this type of reasoning was most prominent when students discussed the subject of mechanisms. Proposing a mechanism is a difficult task for many students (O'Dwyer & Hanly, 2010), and even incoming graduate students in organic chemistry are often unable
to propose mechanisms using chemically-relevant reasoning (Bhattacharyya & Bodner, 2005). Students tend to focus on structural changes rather than process-oriented attributes when proposing mechanisms. It is possible that their limited ability to use reaction mechanisms was due to their lack of a fully-realized mental model of the representations that they manipulate when proposing a mechanism (Strickland, et al, 2010). For this reason, it is not surprising that students most frequently reasoned by using symbol-based reasoning when discussing mechanistic pathways, and it confirms prior research which suggests that students do not have a conceptual understanding of the driving forces behind reaction mechanisms.

Overall, the problem tasks that students face in chemistry can often be solved using one or more analytical methods of reasoning (Kraft, et al, 2010; Lythcott, 1990). There are different motives for why students might use each type of reasoning, and there is not one method of reasoning that is inherently better or worse than any of the others, as each method of reasoning has its benefits when used at the appropriate time. Students are likely to use the method of reasoning that will minimize cognitive demand while still helping them to find the correct solution to a problem (Kool, McGuire, Rosen, & Botvinick, 2010). The role of chemistry instructors should be to help their students understand the strengths and weaknesses of different ways of thinking within the discipline.
CHAPTER 4: CONCLUSIONS, IMPLICATIONS, AND FUTURE WORK

Summary of Results

This dissertation research investigated three main dimensions pertaining to independent student study groups within organic chemistry. First, we investigated how students socially regulated the learning of those within their group. We found that student primarily engaged in three types of interactions: co-construction, tutoring and teaching. Although overall there was no significant difference regarding the prevalence of each interaction, individual groups varied considerably with respect to their engagement with each of the three interactions. Secondly, we looked to see to what depth students discussed the organic chemistry content. In this respect, we found that students primarily engaged in low levels of content processing (remember, understand, and apply). Finally, we saw that students justified their decisions using several different methods of reasoning. The most common ways for students to reason included rule-based reasoning and case-based reasoning.

This research was also interested in characterizing the conditions under which these dimensions were observed. To this end, we found that there were several task and group composition features which affected how students interacted with one another as well as with the organic chemistry material at different levels of content processing. Additionally, we found that symbol-based reasoning, rule-based reasoning, and case-based reasoning tended to coincide with the lowest levels of content processing, while model-based reasoning elicited higher levels (in particular, mechanistic analysis). The methods of reasoning that were exhibited by students tended to coincide with specific
types of content on which the group chose to focus. Finally, we saw that social regulation played a minimal role in influencing the types of reasoning in which groups participated, although tutoring and teaching interactions were twice as likely to elicit model-based reasoning as was co-construction.

Conclusions

Although the behavior of each study group differed depending on a host of factors, several overall trends regarding the nature of these study groups could be observed. For example, we saw that these groups predominantly took a strategic approach to studying (Entwistle, 2000). By relying on instructor-provided problems and study aids, students minimized the effort involved in selecting study tasks and strategically aligned themselves to prepare for the types of problems most likely to be seen on an exam. In general, groups relied on instructor-provided problems, and did not show significant metacognition when deciding which specific tasks deserved greater allocation of time. This was reflected by the many cases in which students worked linearly through a problem set without reflecting on which problems would be most beneficial to address within their study session.

Additionally, we saw that students were strategic with their time, often using their study partners as resources that could be drawn upon to efficiently teach material and answer questions. When students found themselves with questions pertaining to the chemistry material, they could ask their group members for help rather than wrestling with the question themselves in an attempt to reach an understanding. In this way, students relied upon their peers to act as experts and to simplify tasks. We found that
students tended to organize their groups in such a way as to either benefit from an expert (by passively listening to this individual teach material) or by efficiently working on problem sets as individuals, and only asking questions as needed. When they worked collaboratively, students would frequently rely on others to act as experts by asking questions and seeking help. It was far less common for students to purposefully organize their group in such a way as to encourage co-construction. In this way, students only participated in the more time-consuming process of co-construction under circumstances where direct sources of information were absent.

Finally, we saw that students relied on primarily either rule-based or case-based reasoning when discussing chemistry content. Only a few individuals in the study groups exhibited model-based reasoning, and when they did so, they tended to use it merely as an explanatory tool to help others understand a concept. By relying on RBR and CBR at low levels of content processing to discuss the majority of chemistry concepts, students minimized the cognitive demand of the tasks on which they worked.

There may be several reasons why students adopted a strategic approach to studying. One of these reasons could be the nature of the organic chemistry course, which required students to become familiar with large amounts of information pertaining to chemical substances and reactions within a short period of time. Due to the necessity for students to become familiar with vast quantities of information prior to their exams, students may have adopted a strategic approach in order to most efficiently learn the required information. As many groups chose to begin their study process just a few days
before the exam, they may have felt further pressure to study the chemistry material in a more strategic manner.

Additionally, the presentation of chemistry content likely affected how students reasoned about problems. For example, although many different subjects were covered within the first semester of organic chemistry, the majority of prompts tended to elicit discussion pertaining to either representational or structural aspects, which are static characteristics of a more complex chemical system. This is not unusual, as many chemistry courses stress students’ understanding of concepts but fail to demonstrate the relationship between different ideas (de Vos, van Berkel, & Verdonik, 1994). Thus, the organic chemistry course likely focused on, for example, structural aspects without linking this concept immediately to other areas such as reactivity or reaction mechanisms. Because of this lack of coherence among topics, students were able to discuss the material using a series of rules or cases, and did not need to use a more unifying model to talk about the relationship between concepts.

Assessment practices within the course also likely affected how students prepared for their exam (Gibbs & Simpson, 2004-05). Students often prepared by working on practice exams or problems provided to them by their instructor, which mirrored the types of tasks they were likely asked to perform on an exam. These problems tended to elicit low levels of content processing, as students worked primarily at the levels of application or knowledge. As students were not explicitly required to demonstrate higher levels of content processing, they often failed to discuss the content in that manner. Additionally, by working from old exams, students catered their studying to the exact
type of problems that they were likely to see on an exam. This overlap between exams and instructor handouts likely accounted for deficiencies within student studying, as groups limited their studying to address only the concepts most likely to be tested (Thomas, Bol, & Warkentin, 1991).

Finally, students in the observed study groups were likely to make strategic study decisions based on their motivation for performing within the course (Biggs, 1987; Elliot, McGregor, & Gable, 1999). The organic chemistry course is a required class for many science and engineering students interested in pursuing careers in the fields of health and science. Yet for many students, the lessons that are taught within organic chemistry do not apply directly to their field of interest, and often the course is comprised of only a minority of students who are chemistry majors. Thus, students may have had a motivation to perform well in the class so as to achieve a high course grade, rather than achieve a deep understanding of the chemistry content. To this end, it is likely that students adopted a strategic approach to maximize their results while minimizing the amount of cognitive effort involved.

Implications

Considering students’ focus on lower levels of content processing, their preoccupation with rule- and case-based reasoning, and their seemingly unintentional participation in the co-construction interaction, several suggestions can be made to the chemical education community. In particular, by keeping in mind the several factors that may have influenced students’ strategic approaches to studying, we can recommend that educational practitioners address several deficiencies within student studying.
First, we saw that students relied heavily on materials provided to them by their instructors. These included study guides, problem sets, and lists of reactions to review. While these may have been beneficial in helping students to target their studying to the intended concepts, we saw that these study aids often led to low levels and low diversity of content processing. We recommend based on our results that instructors pose problems for students that would elicit a variety of levels of content processing and types of reasoning. Consideration should be given so that tasks require students to move beyond algorithmic application to consider nuanced relationships between concepts. Particularly within the first half of the semester, consideration should be given so that representational and structural aspects are linked to other issues of importance to organic chemists, such as reactivity. While specific reactions may not be introduced until later in the semester, driving forces behind these reactions may be introduced early on. For example, at the same time that ring strain is discussed as a structural feature of different-sized rings, this strain may also be used to discuss a potential driving force behind a reaction (decrease in enthalpy when eliminating ring strain).

We also suggest that instructors provide their students with opportunities that require them to reason using model-based reasoning. By requiring students to support their problem-solving decisions with chemical principles or models, we can not only make students’ thinking about such concepts visible, but we are likely to improve their mental models as well (Buckley & Boulter, 2000).

Students are likely to continue to study in the manner that minimizes their cognitive load, unless assessment measures are changed as well. Assessment practices
should be modified to deemphasize problems that require simple application of ideas, and instructors should instead diversify the focus of their exams to assess for students’ abilities to analyze, interpret, and create.

Within the classroom, students should be given opportunities to actively participate in the modeling of chemical ideas, and to collaboratively co-construct a chemical understanding with their peers. Model-based reasoning will not occur spontaneously, and the more opportunities that students have to think about and make decisions using chemical models, the more likely they are to generate explanations and justifications using MBR as they study in their groups. Consideration should be given in particular to the area of reaction mechanisms. Students frequently demonstrated an inability to reason about mechanisms using chemically-relevant reasoning, and particular attention should be paid to help students to understand the chemical relevance of different factors that might affect a reaction mechanism.

Finally, we see that our research has implications for educational researchers as well. While most of the research pertaining to students’ approaches to learning or study tactics have come from student self-reports of study practices (Biggs, 1987; Entwistle & Ramsden, 1983; Hadwin, Winne, Stockley, Nesbit, & Wosczyna, 2001; Tait & Entwistle, 1996), this study has been unique in the sense that we were able to use direct observation to analyze students’ approaches to learning and the different qualitative aspects of their study behaviors. Our research has shown that it is possible to gain valuable qualitative data from first-hand observations of study groups. When considering that students are not always able to self-report accurately (Winne & Jamieson-Noel,
2002), it may be of particular value to use observational data to ascertain the methods of studying that students use within their groups. If we are interested in helping students to improve their methods of studying, the first step in doing so would be to gain an understanding of the ways in which students prepare for their course. The more qualitative data that we have to support what we know about how students prepare for and think about chemistry content, the more likely it is that we will be able to propose future interventions for these students. Therefore, we recommend this method of data collection for educational researchers who wish to investigate how study groups operate within an authentic environment.

Future Work

There are several areas of future research that could be extended from this project. Considering the dependence that students had on instructor-provided resources, it would be a valuable exercise to examine how different study groups approach their study sessions when provided with different types of study tools. We would be interested in investigating how much of an effect it would have on a group when given different types of prompts. It would be our expectation that students who are working from traditional problems would use a different set of skills than those who are working from more targeted problems that require students to demonstrate their reasoning abilities in more explicit ways. In particular, we would be interested to know if such problems would have the capacity to increase levels of co-construction as groups collaboratively work to comprehend a non-traditional problem.
We found in our study that certain types of problems elicited very specific types of reasoning. In other cases, problems did not strongly elicit any single type of reasoning. Mechanism problems were an example of this latter type of problem, as students approached these tasks in a variety of ways. Future research might additionally be interested in more closely investigating how students reason about mechanistic tasks, with attention paid to what different features bring about each type of reasoning. It would be interesting to compare students with varying level of expertise to determine how formal instruction shapes the way that they think and reason about mechanistic tasks.

Finally, future efforts may be to re-examine some of the un-analyzed data that we have collected. In our study, we paid attention to those instances when students were on-topic and discussing chemistry content. Yet the groups that we observed spent a significant portion of their time involved in other activities, such as socializing, or discussing exam expectations. We may be interested in characterizing what happens within a group as a whole, in order to understand the full context of the study group. It appears as though the study group may have served more than the obvious purpose of helping students prepare for their upcoming exam. Students also appeared to create support networks that were useful in motivating one another to continue their studies. Future efforts may seek to examine the context of the study group in order to characterize some of the less obvious benefits or detriments of group work outside of the classroom.
APPENDIX A: CHEMICAL REASONING IN FIRST SEMESTER ORGANIC CHEMISTRY

Students who take first semester organic chemistry are expected to understand and apply several rules, cases, and chemical models corresponding to the course content. This section will outline some of the representative types of reasoning that students might be expected to use in their application of organic chemistry.

When responding to any problem in organic chemistry, a student must make decisions about how to approach the problem. The student needs to be able to choose a type of reasoning that is most appropriate for each problem, and they must also be able to apply it correctly. A correct application requires an understanding of the nature of the model, case, or rule, as well as an understanding of its range of application.

Model-Based Reasoning

Several models exist which chemists and students can use to reason about chemical concepts. In general, these chemical models pertain to either properties of a compound or factors related to its reactivity. In both instances, models are used to understand the nature of a chemical compound and to predict its behavior. The following section will describe several different models to which students within their first semester of organic chemistry may be exposed. This does not represent a comprehensive list of all chemistry models, but rather, a list of the major models that students might be expected to reference.
Two important and complementary scientific models that describe chemical structures are the valence bond (VB) theory and the molecular orbital (MO) theory. Both theories describe and explain aspects of chemical bonding using quantum mechanics. Within the valence bond theory, it is believed that covalent bonds exist in instances where two half-filled atomic orbitals overlap. Orbitals represent regions in space where it is most probable to find an electron; therefore, electrons within a bond are likely to be found in the location where the orbitals overlap. Two types of covalent bonding are possible: sigma (σ) and pi (π) bonding. Within the sigma bond, orbital overlap occurs such that the bond is head-to-head between two atomic orbitals, and aligned along the bond axis. The pi bond, on the other hand, represents an overlap of atomic orbitals that occurs above and below the molecular plane. This type of sideways overlap in the pi bond accounts for double or triple bonds, whereas all single bonds are sigma bonds (Figure A.1).

![Sigma and pi bonding](image)

Figure A.1. Sigma and pi bonding

In order to understand the geometry observed for certain types of organic molecules (notably those with tetravalent carbon atoms), the VB theory incorporates hybridization into its theory. Within hybridization, s and p atomic orbitals may be mixed together to form new hybrid atomic orbitals. For example, if one p orbital and three s orbitals around the same atom are hybridized, they would form four identical sp³ orbitals, for which one quarter of the orbital is attributed to s-like character, and three-quarters of
the orbital is attributed to p-like character. In the case of methane (CH₄), the existence of four identical sp³ hybridized orbitals would explain the tetrahedral geometry predicted by VSEPR (valence shell electron pair repulsion) theory.

The molecular orbital theory contends that bond formation occurs as atomic orbital overlap increases until the point at which the orbitals combine to form new molecular orbitals (bonding and antibonding). The new molecular orbitals encompass both nuclei involved in the bond. Thus, unlike the VB theory, the position of the electrons in the bond may extend across the entire molecule. In some cases, the MO theory may be used to explain features that might otherwise be unaccounted for through the VB theory. For example, through MO theory, we can explain the reactivity of photochemical reactions.

Both the valence bond and molecular orbital theories help one to understand the basic principles of chemical structure that may be encoded in different representations of the molecule (for example, the 2-D lewis structure or 3-D ball-and-stick model). Additionally, both theories include further information which may be helpful in determining properties or reactivity of a species. For example, the type of hybridization of a hydrocarbon molecule may be used to predict its level of acidity. Or in other cases, consideration of molecular orbital overlap would help to explain Diels-Alder reactivity.

Additional scientific models in organic chemistry add to our understanding of molecular structure and reactivity. An idea of central importance to organic chemists is that of electrostatic interactions, which account for much of the attractive or repulsive forces between and within molecules. Simply put, this idea states that charges on an
atom will be attracted to oppositely-charged species. The actual force of attraction
between charged species may be accounted for using Coulomb’s law ($F = \frac{q_1q_2}{r^2}$) where the
greater the charge of a species ($q$) or the smaller the radius ($r$), the greater the force ($F$) of
attraction will be. Electrostatic interactions account for intermolecular forces between
species; for example, within the dipole-dipole interactions, the partial positive charge of
one compound is attracted to the partial negative in another. Additionally, these
electrostatic interactions may account for reactivity between species, which is the case
when the negative charge of a nucleophile is attracted to the partial charge of a carbon in
a substitution reaction.

Electrostatic interactions are often due to differences in electronegativity between
atoms. Electronegativity may be defined as the ability of an atom to attract electrons.
Therefore, an atom which has high electronegativity may have a partial negative charge
(due to increased electron density) compared to another atom which has low
electronegativity. Differences in electronegativity account for such things as bond
polarity or inductive effects.

The inductive effect is an observed phenomenon in which the electron density of
a molecule shifts in response to the electronegativity of nearby atoms. For example,
within ethyl fluoride, the fluorine atom will pull electron density away from both carbons
in the structure, due to its high electronegativity. As a result, both carbons will have a
partial positive charge, even though only one carbon is directly bonded to a more
electronegative atom. Similarly, groups which include an atom with a full or partial
positive charge will inductively pull electron density in its direction. For example, within
nitroethane ($\text{CH}_3\text{CH}_2\text{NO}_2$), the nitrogen atom has a full positive charge on it. This leads to an electron withdrawing effect, where electron density is pulled away from both carbon atoms to account for this difference in charge.

Resonance theory is similar to the inductive effect in that it accounts for partial charges, electron withdrawing, or instances of electron donating within a molecule. This theory states that when it is possible to represent a molecule using two or more Lewis structures which differ only in the placement of electrons, the actual molecule will be a hybrid of these structures. Each individual Lewis structure is incomplete on its own, though a weighted average of each resonance contributor leads to the overall structure of the molecule. Resonance explains why each carbon-carbon bond within benzene is equivalent in length, or why the negative charge of the nitrate ion ($\text{NO}_3^-$) is evenly distributed among each oxygen atom. Resonance may also help to explain certain acid/base trends. For example, phenol ($\text{C}_6\text{H}_5\text{OH}$) is more acidic than cyclohexanol ($\text{C}_8\text{H}_{11}\text{OH}$) due to the resonance stabilization of the conjugate base. The oxygen in phenol is electron-donating, because its electrons may re-distribute within several resonance structures, thereby minimizing the charge that any one atom would hold within the conjugate base.

One final chemical concept which is significant to first semester students of organic chemistry is that of the steric effect. Each atom within a molecule occupies a certain amount of space, and when these atoms come within close proximity of one another, they may experience repulsion due to overlap of electron clouds. The steric effect of a molecule is discussed within first semester organic chemistry in relation to
conformation of a molecule (for example, with respect to possible chair conformations of cyclohexane) as well as reactivity of reactions (for example, steric hindrance within $S_N2$ reactions).

Although additional chemical models exist within organic chemistry, we believe that these are some of the more significant principles for first semester students. In certain situations, students may reason using just one of these types of models, although in others, students may be expected to use multiple models as justification for their decisions. For example, when determining relative acidity of compounds, an individual must consider the sometimes competing factors of resonance or inductive effects.

**Case-Based Reasoning**

Students may use a number of cases to reason through organic chemistry concepts. Perhaps the first type of case that students are exposed to is the classification of chemical substances. Classification is an important aspect of chemistry, and types of classification may range from the very general (such as molecular or ionic substances) to more specific subgroups. Within the organic chemistry course, students are taught several different functional groups which can be used to classify molecular substances according to their properties. A functional group represents a case, because it classifies a structural feature into a category that may be common to many compounds. For example, in Figure A.2, several structures exist which share the common functional group of alcohol.
Commonly, students may also think of generic reaction types as examples or cases that would apply under similar conditions. For example, the halogenation reaction is one in which two halogen atoms are added to carbons in either an alkene or alkyne functional group. If students are able to identify the type of reaction (halogenation) and understand the conditions under which it is applicable (double or triple bonded carbons), they are likely to be able to apply this case in many different circumstances. Many reactions that students work from in first semester organic chemistry are either named reactions or they correspond to a specific type of functional group transformation. For example, reactions may be organized according to the type of functional group within a reactant (e.g., hydrohalogenation, halogenation, oxymercuration, and hydroboration are all reactions that may be initiated from an alkene functional group). In other cases, reactions may be organized according to the functional group in which they result (e.g., alkene or alkyne formation). Finally, reactions may be classified according to their mechanism (e.g., $S_{N}1$ and $S_{N}2$ reactions correspond to substitution reactions that involve either two or one major mechanistic steps, respectively). Students may use cases of reactions in order to predict the product of a reaction or to recall the generic mechanism attributable to a reaction type.

Other aspects of organic chemistry may be thought of as cases. For example, splitting patterns within NMR spectroscopy may be classified as cases belonging to
certain hydrocarbon fragments. A student may remember, for example, that a quartet with integration of 2 in conjunction with a triplet with an integration of 3 represents an ethyl fragment (see Figure A.3). Similarly, students may commit other splitting patterns to memory as they become more familiar with NMR spectroscopy so that they do not need to go through the process each time of determining the relationship between splitting patterns and structure through a rule-based process.

Figure A.3. Example of NMR splitting that would be characteristic of an ethyl fragment. In this case, the example corresponds to CH₃CH₂Cl.

A final example of how students might use case-based reasoning in their course is with respect to chair conformations. For example, a student may recall that when a line structure is given for cyclohexane, there are specific cases that can be referenced in order to determine whether the substituents will be axial or equatorial without having to draw the chair conformations. For example, if both substituents are on odd-numbered carbons and are either both wedges or both dashes, the resulting lower energy chair conformation would have two equatorial substituents. Similarly, if two substituents are on adjoining carbons (one odd-numbered and the other even-numbered), and one is a dash and the other a wedge, the chair conformation would also have equatorial substituents. If
students remember these cases, they are able to apply this information to new line structures without having to go through the rule-based process of drawing the chair conformations each time.

Rule-Based Reasoning

Students are exposed to many rules within organic chemistry. Some of these rules come in the form of facts, and others in the form of procedures that may be applied under specific circumstances. Although instructors likely impart their own rule-based reasoning to their students, we will give some examples here of commonly-cited rules within the field of organic chemistry.

Nomenclature is perhaps the most obvious example of rule-based reasoning that chemists may perform. In particular, IUPAC (International Union of Pure and Applied Chemistry) nomenclature is intended to provide a method of communicating names of chemical structures in a systematic and coordinated manner. As such, there are several rules that one may follow in order to name an organic compound. For a simple alkane structure, one would have to 1) identify the longest carbon chain (the parent hydrocarbon), 2) identify and number the substituents, and 3) write the name as a single word, using proper conventions.

A second rule-based method which is used to determine a structural feature in a systematic manner is the Cahn-Ingold-Prelog priority system. This set of rules is used to determine whether a stereocenter is “R” or “S,” and is used to determine whether a double bond may be categorized as “E” or “Z.” For example, in order to determine the configuration around a carbon atom, one would have to assign a priority to each of four
substituents based on atomic number, at which point the structure is rotated so that the
group with the lowest priority is directed away from the viewer. Finally, the remaining
three substituents are considered in order of highest to lowest priority. If they are
arranged in a clockwise manner, the designation is “R,” otherwise the stereocenter is
labeled as “S.” This naming system has been incorporated into the IUPAC nomenclature
system and allows for structures to be referenced in a more stereo-specific manner.

Additional rules are cited with respect to chemical reactions. For example, the
Zaitsev rule states that if more than one alkene can form in a given reaction, the major
product will come from the more stable product (the alkene with the most highly
substituted double bond). In another example which extends from the Zaitsev rule, the
Markovnikov rule states that if a protic acid (HX) is added to a double bond, the
hydrogen will add to the carbon with the greatest number of hydrogen atoms already
attached. Both rules may be considered when determining products in a reaction.

Instructors may also suggest rule-based systems that can be used to help their
students navigate through different subjects. Students may be advised to use a systematic
rule-based approach when determining the relationship between two structures. For
example, students may first count the number of atoms in two structures to determine if
they have the same molecular formula. Then they would look at each atom to see if it has
the same connectivity compared to the other structure. If it does, then they are either
identical or stereoisomers. If the connectivity is different but the two compounds have
the same molecular structure, they are constitutional isomers. Students can follow a
decision tree such as this to determine the relationship between two different structures.
In other examples, it may be recommended to students to use a systematic method for converting line structures to chair conformations or for determining a chemical structure from spectroscopic data (NMR or IR).

Examples of Student Reasoning

In this section, we will provide examples of tasks that could be seen within first semester organic chemistry and which could elicit responses either from rule-based, case-based, or model-based reasoning. We will provide three problems and give examples of potential student responses that would lead to the correct solution.

A person could approach the task described in Figure A.4 in a number of different ways. A student using rule-based reasoning might describe their thought-process as follows: “Both structures are similar, except that in the first example, the acidic hydrogen is attached to an oxygen, and in the second structure, the acidic hydrogens are attached to the nitrogen. I know that the periodic trend for acidity increases as we consider atoms to the right and down on the periodic table. Because oxygen is in a group further to the right on the periodic table than for nitrogen, it is likely that the first structure is more acidic than the second.” This hypothetical student would be using a rule (the periodic trend) to determine relative acidity.

Which compound is more acidic?

![Figure A.4. A prompt which requires students to determine which compound is most acidic.](image)
Similarly, a student might use case-based reasoning when determining the answer to this problem. An example of such reasoning would be: “The first structure is an example of a carboxylic acid, whereas the second structure is an amide. I know that in general, carboxylic acids are more acidic, so I predict that the first structure is most acidic.” This student would be classifying each compound relative to its functional group. This would allow the student to consider properties in terms of classes of types of compounds, rather than consider each structure as a unique compound.

Model-based reasoning would look similar to this: “Both structures are relatively similar, although the oxygen on the first structure is more electronegative than the nitrogen of the second structure. Because it is more electronegative, the oxygen has a greater ability to attract electron density toward it. It would therefore have a more polarized bond with hydrogen, so that the hydrogen atom would have a greater partial positive charge, which would make it easier to dissociate in the presence of a base. Additionally, because it is more electronegative, the oxygen atom will accommodate the negative charge of the conjugate base more readily than nitrogen. Therefore, structure one is more acidic.”

In another example, if a student were to use rule-based reasoning in response to the prompt shown in Figure A.5, this person would likely systematically go through a set of procedures in order to determine the most stable chair conformation. A student’s response might look something like this: “I am going to start by drawing a generic chair with axial and equatorial substituents. The ethyl side chain will be the bulkiest, so I will start by placing that in an equatorial position. Next, I will determine that the bromine
substituent is two carbons away from the ethyl substituent. In order to keep both substituents pointed in the same direction, bromine must end up in an equatorial position as well.”

For the following structure, draw the most stable chair conformation.

![Figure A.5](image)

Figure A.5. A prompt requiring students to translate a representation.

This student would be using a systematic methodology in order to draw the chair conformation, position the substituents on the correct carbons, and draw the correct stereochemistry (Figure A.6). This type of reasoning demonstrates how a series of rules may be implemented in order to solve a problem.

![Figure A.6](image)

Figure A.6. The order of structures drawn by a student using rule-based reasoning in order to come to a solution for a chair conformation problem.

A student using case-based reasoning might explain their thought process as follows: “In the given structure, the bromine and ethyl substituents are both on odd-numbered carbons, and they are both wedges. When these conditions are present, I know from experience that this will lead to a situation where both substituents are equatorial in the most stable chair conformation. Therefore, I will draw the final chair conformation with both substituents as equatorial, and on carbons one and three.” This hypothetical
student would have bypassed rule-based reasoning, because the student recognized the circumstances under which the conformation would have two equatorial substituents.

A student using model-based reasoning in this problem might, for example, use a model kit to determine relative stability of chair conformations. This student might reason in the following manner: “If I build a model of this molecule, I can compare the two possible chair conformations. It looks like these two substituents would be either both equatorial or both axial. In the axial position, there would be unfavorable steric interactions as the two substituents are in close proximity to one another. The equatorial positions would be more stable, so I will draw my chair conformation with both the bromine and ethyl groups in the equatorial position.” This example demonstrates model-based reasoning in two different ways. The student used a model kit to consider the placement of atoms in a 3-D structure. Secondly, the student mentioned the concept of steric effects and used this as justification for the more stable structure.

A student working through the mechanism problem below (Figure A.7) might use rule-based reasoning on several occasions in order to determine the mechanism for a reaction.

Predict the product of the following reaction and write a mechanism to explain the product.

![Reaction](image)

Figure A.7. A problem requiring students to draw a mechanism and predict the product of a reaction.
A student might say: “I know that the hydrogen will add to the less substituted carbon because of the Markovnikov rule. For the intermediate, the more substituted carbon in the double bond would have a formal charge. That can be calculated by taking the total number of valence electrons that the carbon has (4) and subtracting the number of bonds (3) as well as the number of nonbonding electrons (0). That leaves us with a formal charge of plus one on the intermediate. In the final product, the bromine will be connected to the most substituted carbon. In drawing the mechanism, I need to draw the curved arrows originating from a source of electron density, so in the first step, the curved arrow will originate from the double bond. In the second step, the bromine will have a negative charge, so I can draw a curved arrow from the bromine to the carbocation.” In this example, the student used rules to determine structural features (such as the formal charge) and rules regarding the arrow-pushing formalism in order to draw the appropriate mechanism (Figure A.8).

![Chemical structure](image)

Figure A.8. The correct mechanism and final product corresponding to a required mechanism task

A student using case-based reasoning would recognize the above reaction as an example of hydrohalogenation. An example of a student response might be the following: “This is an alkene reacting in a hydrohalogenation reaction. I know that the final product will add the hydrogen and bromine to the double bond, and the hydrogen will add to the less substituted carbon. This reaction also has an intermediate. Hydrogen
adds first, and there will be an intermediate with a carbocation on the more substituted carbon. To draw the mechanism, I can simply draw arrows to account for the changes in structure between the initial reactant and intermediate, and between the intermediate and final product.” This student would most likely draw the structures of the intermediate and product first, as these are pieces of information that pertain the closest to the case that they are recalling. Next, the student would finish the mechanism by indicating the movement of electrons through the arrow-pushing formalism.

Model-based reasoning would likely result in higher considerations of reactivity. A student might say the following: “The double bond has high electron density. This will be attracted to the hydrogen, which has a partial positive charge due to the polarized bond in hydrobromic acid. A carbocation would likely form on the more substituted carbon, as it would be more stabilized by the presence of the three alkyl groups attached to the carbon. Thus, the intermediate would have a tertiary carbocation. Finally, the negative charge of the bromine would be attracted to the positive charge on the carbon. This force of attraction will result in the final product.” The students using model-based reasoning may be more likely to explain each step of the reaction, and to include explanations for why the mechanism proceeds in the given manner.
APPENDIX B: FURTHER DESCRIPTION OF CODING SCHEME

This section will describe in greater detail the codes that were used to apply to the study group transcriptions. The applied codes identified types of student interactions, levels of content processing, methods of reasoning, subject matter, and prompts from which groups were working. Each of these sets of codes will be described in further detail.

Student Interactions

Three student interactions were identified and coded as co-construction, tutoring, and teaching. Within the co-construction interaction, several individuals discussed the chemistry content in equivalent ways. They may have been brainstorming, building ideas, or coming up with explanations together while using each other as a guide. In these instances, each participating member of the group was working to align their chemistry understanding with the ideas of others in their group. In certain cases, one student posed a question, and in the course of responding to this question, two or more students may have progressed into a co-construction interaction as they worked together to align their ideas. Thus, co-construction may have come in response to an individual of the group who posed a question. In certain cases, the individual posing questions may also have contributed to the co-construction interaction. For example, if students were arguing opposing points, the student asking questions may have been asking critical questions that opposed another group member’s viewpoints, or forced this person to reconsider a task in a new light. In the excerpt below, student “A” began with a question, but she
continued to participate in the brainstorming process in order to contribute to the solution to her question. In this way, the students did not adhere to specific roles but rather contributed in equivalent ways to collaboratively reach a solution.

A: I have a question. If we were given a structure and we had to say what the functional groups are, are those two like, amides put together or?
Y: I mean you might be able to call them each separately amines. I don’t know. I’m not very good at recognizing them.
A: Aren’t the amides are, aren’t the amides the ones that are like R, like R, O, and then NH2? Or this could be NHR or NR2? (draws picture of generic amide) And then the amine is RNH2?
Y: Yeah, exactly. So like, should we just count this as one big fat amide?
A: Well, this isn’t an R, though.
Y: The R can just be any blob of atoms, right?

One last manner in which co-construction was exhibited occurred when students of the study group were already aligned in terms of their understanding of chemistry content. They may have been discussing a topic which was understood by all members of the group; for example, if each student was suggesting personal methods for approaching and solving a problem. Under these circumstances, the driving force of the co-construction interaction was not to learn a concept as a group, but rather, to review material or for each group member to offer tips for approaching a task. For example, in the passage below, two students co-constructed even though they both had an understanding of how to determine hybridization. They compared methods of approaching the same task and found that they had similar approaches.

L: And so when you’re doing the hybridization, okay, the way I think of it is think of how many things are coming off of it. And if there are four things coming off of it, isn’t it sp3? And then three things it’s sp2 and two things it’s sp1.
Y: Yeah, that’s exactly how I think of it. I don’t even try to visualize like p-orbitals. I’m just like, three things.
L: Yeah, because that’s how we learned it last semester, but he never said that, so yeah. I think it’s better to be able to visualize it, but.

Under all circumstances where co-construction was observed, multiple students were contributing ideas; and although all parties might not have been participating at equal rates, the role of the participating students were essentially equivalent.

The tutoring interaction was reflective of a question and answer transfer of ideas. When tutoring, there were specific roles to which students might have adhered. There was a student who posed a question or a topic, thereby controlling the content that was discussed. Additionally, there was a student who responded to this question by providing an explanation. Not all questions that were asked resulted in a tutoring interaction, so it was important to consider the context under which students were conversing. For example, students frequently used questions as the vehicle for suggesting ideas (Volet, Summers, & Thurman, 2009a). The tentativeness of the question allowed them to propose a solution to a task while allowing the possibility for others to contribute ideas as well. This could lead to co-construction rather than tutoring, because the goal of the question might not be to seek the expertise of another in the group, but rather to contribute a suggestion.

In order for a conversation to be reflective of a tutoring interaction, students needed to exhibit specific roles of either requesting information or giving information. It was common for a tutoring interaction to chronologically follow either a co-construction or teaching interaction. In these circumstances, a student might wish to ensure their understanding of a subject, and would therefore pose a question or two to ascertain their mastery of the topic. When coding such instances of the tutoring interaction (which
could potentially be brief exchanges), we looked for at least two consecutive questions in order to assume a shift to a tutoring interaction. For example, the excerpt below indicates how students shifted from a teaching interaction to a tutoring interaction. The first three lines of dialogue represented the conclusion of a teaching interaction, whereas the next several lines indicated the beginning of a tutoring interaction. Within this excerpt, student “Y” shifted from being a passive recipient of information to actively asking questions and controlling the direction of the conversation.

A: So if this is a p orbital. If this is a y p-orbital, for instance, it would look like this, like this is going forward, this is going backward, this is going straight up and down, and then this is going straight to the side. But then if it’s sticking this way, then it likes them to be like this. Does that make sense?
Y: I think. You’re sticking the p-orbital a different way. Is that what you’re saying?
A: Yeah, because now the p-orbital is sticking out towards us and then back into the plane? So that’s why
Y: Yeah, yeah, that’s right then. And I remember, you said a py corresponded to a pz. Like how are they bonded?
A: Well I think that’s a pz orbital.
Y: That’s a pz right there?
A: I think it should be a pz that only connects to a pz. The pz only connects to pz, and the py only connects to py.
Y: So then this has to be pz so that it can be bonded with that?
A: I think so.

Within the teaching interaction, an individual within the group exhibited an instructive role, and this student determined what content would be discussed. This student then taught by lecturing the chemistry content to the rest of the group members. Oftentimes, this left the rest of the students in the group as mere passive recipients of the information, and their contributions to the group were minimal. In this way, the individual who was teaching may have lectured about a topic without pausing to ascertain
that others in the group had understanding. In other cases, the student who was teaching may have walked an individual through a topic by explaining concepts but also by posing frequent questions. They may have asked such things as, “How would you do the next step?” or “What do you think this means in terms of X?” In this way, they required others in the study group to respond and participate, although the student doing the teaching still determined the content that was discussed. In the example below, student “O” walked his study partner through a nomenclature problem, although he required her to answer questions and participate in creating the solution.

O: So. You’ve got these numbered then. So. Name the substituents off the main mother. (pause)
K: 4-ethyl, 2-methyl, uhhhh.
O: What are you doing? You’re still naming this, right? There you go.
K: Cyclo
O: That’s the name of it, right? And it’s attached to
K: It’s attached to . . . one.
O: There you go. One dash, okay. So you’ve identified everything now.

Students with opposing viewpoints also engaged in the teaching interaction. In these cases, an individual with an opposing viewpoint often corrected another in the group. If their suggestion was immediately agreed-upon (and did not generate discussion from multiple parties), this might be an example of the teaching interaction. Overall, when students participated in the teaching interaction, students adhered to specific roles, and the person explaining a topic was the one who determined what content they wished to focus on.
Levels of Content Processing

The codes in this study pertaining to students’ levels of content processing were based on a modified Bloom’s Taxonomy (Krathwohl, 2002) and included codes for remember, understand, apply, analyze, and create. The code for remembering was indicative of instances where students recalled memorized information. For example, knowledge about a topic might be stated, and if could be easily used to solve a problem without requiring much integration or data processing, it would be coded as remembering. In the example below, students simply recalled information pertaining to the identity of a functional group in question.

\[ R: \text{This is an amine, right?} \]
\[ P: \text{NH}_2 \text{ I think it is.} \]
\[ R: \text{Amine, right?} \]
\[ P: \text{It’s an amide? Yeah, double bonded to the oxygen.} \]

Understanding was demonstrated when students attempted to determine the meaning of a chemical concept or representation. In order to be coded as understanding, the study group was generally trying to answer a “why” question, or else they were trying to come to a conceptual understanding of the material. Students generally engaged in this level of content processing as they attempted to create explanations for chemical concepts or unexpected data. For example, the students in the excerpt below struggled to understand how isopropyl differed from a propyl substituent.

\[ E: \text{Why is it called isopropyl in this circumstance?} \]
\[ L: \text{What does that mean, that weird line with the squiggly around it? I know it means iso, but I don’t understand what that means.} \]
\[ M: \text{It means it’s attached to something else that could be like, attached to another chain or,} \]
\[ L: \text{Oh, okay, and it’s attached to the middle carbon, that’s why it’s isopropyl?} \]
E: Well it doesn’t say it’s connected to anything, it’s just connected to something and they call it isopropyl.
L: Yeah, but see the bond is made to that middle carbon, right?
E: Is that important?
L: Yeah, that’s why it’s the isopropyl.
E: Oh, okay, so if it was attached over here it would just be the propyl?

Students generally applied information in one of two ways: they either executed an algorithm or implemented a general concept in a new situation. If students executed an algorithm, they worked through a well-developed procedure in which they could follow specific steps in an orderly fashion. If students were implementing a concept, they applied information to a new context. They may have extrapolated information from a novel situation that would have allowed them to see how the application of a rule, case, or model would fit in this new context. In this type of application, there was not a set procedure to follow, but rather students followed an extension of an idea. For example, the students below tried to determine which conformation of a cyclohexane ring would be most stable when given the A-values for two substituents. The students applied their understanding of what would make a more stable conformation (implementation).

J: So higher kilojoules is more stable always, right?
K: Well no. This is diaxial strain. You want the one to be axial that has the lower number of kilojoules, because it’s telling you the kilojoules of strain. So.
A: So wouldn’t the 2.1 be good?
J: I think it’s 3.8 right?
K: I’m pretty sure it’s the 2.1 one. Because that’s telling you the value of the strain, and you want less strain not more strain.
A: Less is better.

There were several methods of analysis in which students participated. A generic type of analysis required students to break information down into parts in order to discuss a task. Whereas the application of a task would require students to relatively directly
apply knowledge that they knew to a new situation, the analysis of a concept involved a more complex approach. The students involved needed to pay attention to multiple factors or divide a problem into smaller parts in order to understand it better. Several types of analysis specific to organic chemistry also adhered to this definition. Connect-the-dots analysis was demonstrated at times when students worked on mechanistic tasks. They drew mechanisms based on the structural differences that they observed between the reactants and predicted products, without consideration to chemical reactivity. For example, the students below drew a mechanism by considering the structural differences between the product and reactant. They referenced the final structure of the product in order to defend their decisions about leaving groups.

A: Didn’t this give this thing to the O and
C: Then you’ve got Cl hanging out there.
N: Yeah, H came in and broke this bond?
K: Well H came in and attached first. But actually it breaks that bond.
C: H attaches to, um, to the oxygen, on the OH
A: Look, that has to go there because it has to lose that?
N: Cleave that bond.

Mechanistic analysis also pertained to drawing mechanistic steps, although this type of analysis included consideration of chemical principles. Students who used mechanistic analysis explained their process of analysis in more depth and included a description of the sometimes competing chemical factors affecting potential mechanistic pathways. In the following excerpt, students analyzed a reaction pathway by considering the reasoning behind each mechanistic step.

K: Let me see something real quick. Because, yeah, the halides are going to be good leaving groups on their own as long as they’re in a solvent that they like. And so what’s going to happen is you’re going to have a solvent
in which potassium and hydroxide dissociate and the hydroxide’s going to deprotonate the, the,
R: The hydrogen?
K: Yeah, that hydrogen. And then the halide group’s just going to leave.
R: Yeah, so then you have this OH minus floating around in solution with lots of electron density going on to steal this proton.

When working on synthetic analysis, students paid attention to the structural differences between reactants and products in order to propose synthetic pathways. The recognition of structural differences elicited consideration of potential reactions which were able to account for the dissimilarity between reactants and products. The students in the example below demonstrated synthetic analysis by using structural differences to suggest different reaction pathways.

A: Uh huh. So now what we want to do is get rid of that triple bond without flipping that part. So it would be H₂Pd/C. Yeah.
P: Could we do lindlar’s catalyst?
A: No, because that would make it slow down. Oh yeah, we have to do that, nevermind.
P: So it is lindlar’s catalyst?
A: Yeah. So. H₂Pd/C and then Lindlar’s catalyst. Okay, so you’re going to get a double bond.

A final type of content processing was seen when students created. In this category, students compiled information together in order to generate an answer. Whereas within analysis, where students were pulling data apart, within the level of create, students were compiling information and putting it together in order to create something. For example, they may have created a structure which was representative of IR or NMR spectral data (seen below).

A: Well, so there’s a hydrogen attached to the oxygen, you know that. So write down your fragments. Now count what you have so far.
P: Like in this? 1,2,3, and then this connected would be the four.
A: So there is four. (pause) Now, what’s on the other end though? No. What fragment have you not added yet? You have it under your fragments, that’s your first hint.
P: What, the isopropyl? Like that?
A: Yeah, that’s it!

Student Reasoning

Students used several methods of reasoning when discussing organic chemistry content. For example, they used model-based reasoning, case-based reasoning, rule-based reasoning, or they may have simply manipulated symbols (symbol-based reasoning). Appendix A provides a comprehensive description of the first three of these types of chemical reasoning, complete with examples of each type.

Model-based reasoning was exhibited by students who manipulated a chemical principle or theory in some way so as to come to a new conclusion. Such discussion might have centered on a structural aspect (for example, determining whether a bond can rotate, determining a spatial relationship within a molecule, or discussing issues of steric). In other instances, model-based reasoning was used to discuss driving forces of a reaction. Students would describe how molecular strain or electrostatic interactions drove a reaction to completion. For example, in the following excerpt, student “A” described why a structure rearranged by discussing electrostatic interactions.

H: Whoah. Okay, how does that work?
A: Let me see. So that’s the bromonium ion and that has a positive charge. And that’s why, this has a negative charge on it? So this attacks it. So that joins there, and when the positive (something), it had to go here. And then the bromine comes in and takes the hydrogen. Does that makes sense?
H: Yeah, I just don’t see how it turns that into that.
A: This is a partial negative charge, and then that is the bromonium ion, which has a net positive charge down here (drawing on the board). So this comes over and attacks that.
When using case-based reasoning, a group would reason by using a past example or experience that could be applied to a new situation. Students often used a classification system in order to determine what case could be applied to a particular situation. They would classify structures or reagents so as to predict intermediates, products, and/or mechanisms related to a particular reaction. In the following excerpt, two students referred to previous examples in order to comprehend why methoxide could act as a nucleophile in an $S_N1$ reaction. Student “T” referred to a particular problem in which methoxide was the nucleophile, and student “A” referred to her notes which classified methoxide as a good $S_N2$ nucleophile.

T: Okay, so. On this one I guess, the only thing I could think of is it must not be a good nucleophile. Which is strange, because then he uses the exact same nucleophile down here to do an $S_N2$ reaction. Because that’s what [methoxide] is. I don’t understand why that’s wrong.

A: Yeah. Well, and it’s on our list of $S_N2$ nucleophiles. That led me to assume that it would be $S_N2$ as well.

Rule-based reasoning was exhibited by students when they were doing such activities as applying nomenclature rules, defining terms, determining formal charge, translating a representation, or using a particular methodology in order to draw a more stable conformation or determine the structure of a compound represented by NMR data. By using rule-based reasoning, students did not always need to have an understanding of underlying chemical principles. As one instructor noted during a study session, a person could use a rule-based approach to interpret NMR data without having any chemistry background:

I: Not to put down our administrative assistant at all, she’s brilliant, she’s really really smart. But she had no chemistry. I don’t even think she had high school chemistry. But I taught her how to do NMR spectroscopy, or
at least how to interpret them. And the PhD people that I had working for me, they would get their NMRs and just hand them to her, and she would do the structure. She got so good at it. So, no chemistry at all. She didn’t really know the atoms. She just knew what the four things I taught you guys today. Integration, chemical shift, splitting patterns, and how many bonds are on each thing.

If using rule-based reasoning, a student would either discuss the meaning of a rule or apply a series of rules (a methodology) in order to come to some conclusion. For example, in the following excerpt, students discussed the distinction between a meso compound and two structures that are structurally identical. By discussing the differences between these two terms, the students determined the rules that pertained to each.

N: Isn’t identical and meso the same?
E: Are they always the same thing?
N: Well in order for it to be meso, it would have to have a plane of symmetry. And it’s got to have a chiral center.
E: Something that’s identical is not always meso. In order to be meso you have to have at least two chiral centers.
N: At least two?
E: Well, the definition that we use is one. But if you have a meso where you have an internal plane of symmetry, so if you have a chiral center on one side, you’ll have to have it on the other.
N: What if you have it right in the middle?
E: If it’s right in the middle, you don’t have four groups that are all different.

Also of note were those instances where students used symbols with which to reason when speaking to their group members. Symbol-based reasoning was coded for when students failed to provide proper justification for their choices, and merely appeared to manipulate symbols on a page. For example, symbol-based reasoning is represented in the excerpt below as students worked on a mechanism problem:
It would be something like that. And then your intermediates are going to be . . . here. And then Br minus. That’s what the intermediates are. That bond is going to break, it’s going to go here. Okay, well there’s only really one option possible.

A: It can just bond like anywhere on this? That’s what I think.

T: OK. And when you have the intermediates, you don’t. These two electrons will go, this bond will break, and it will go to hydrogen, and this Br will form a bond down here. Oh. Ohh, okay. Yeah. We have to put a positive charge over here.

Many times, the context of the group discussion was used to determine what type of reasoning was being used. For example, if a student merely stated that a particular hydrocarbon was more acidic because of the presence of a double or triple bond, this might be considered rule-based reasoning. But if this student was to go on to explain how the molecule with the triple bond had greater s-character, and described how this led to increased stability of the conjugate base, this segment would likely be coded as model-based reasoning. Thus, much of our coding depended on how much justification a student gave for their choices. We needed to consider the context for which they were explaining their reasoning, and we used this to determine whether or not a student was expressing their reasoning in terms of a rule, case, or model. In certain instances, it was possible that a student may have been mentally making a decision using model-based reasoning, but if they did not make this reasoning explicitly visible, we were unable to assume the presence of such reasoning. Further examples of each type of student reasoning is given in Table B.1.
Table B.1. Further Examples of Student Reasoning

<table>
<thead>
<tr>
<th>Model-Based Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building an explanation</strong></td>
</tr>
</tbody>
</table>
| O:  *Oh! This is an ethyl? Oh, it is an ethyl. Yeah. This is definitely [a] more stable [chair conformation].*  
  K:  *Well, but I wouldn’t be able to know why.*  
  O:  *Well think about a bromo and an ethyl right? So a bromo is just one little thing sticking out and an ethyl is one, two things sticking out. So this is obviously the bigger thing. So you want the bigger thing to be, ahh, equatorial, more stable.* |

| **Predicting a result** |
| R:  *What do you know about this molecule, when it’s just sitting there. Does it stay static, does it move at all?*  
  B:  *It moves.*  
  R:  *It moves, right. So this bond between the carbon and the chlorine, is polar. What could happen?*  
  B:  *It might fall apart.*  
  R:  *It might fall apart. So if it does fall apart, we’re going to have a carbon, which would still have three methyl groups on it. And because it’s now missing that, because the chlorine takes the electrons with it when it goes, you get a carbocation intermediate. Still surrounded by that ethanols.* |

<table>
<thead>
<tr>
<th>Case-Based Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Working from an example</strong></td>
</tr>
</tbody>
</table>
| O:  *Did you say that you understand radical mechanisms?*  
  J:  *It’s the same as the one in the book. Because it looks like it follows like the same pattern when they use Cl in the book?*  
  O:  *That’s a good example. Let’s use Cl. Give me the. . .*  
  J:  *It’s the same thing exactly, except that the Br is the Cl.* |

| **Applying a case to a new situation** |
| D:  *Backside attack is only for S_N2?*  
  A:  *Right, for S_N1 it just falls off.*  
  C:  *This one right here is an S_N2 also.*  
  D:  *Yeah, they switch [stereochemistry], right?*  
  C:  *Yeah.* |

<table>
<thead>
<tr>
<th>Rule-Based Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Defining terms</strong></td>
</tr>
</tbody>
</table>
| N:  *What’s protic and aprotic mean?*  
  A:  *Umm, just meaning, protic is when you have NH or OH in it. And aprotic is when*  
  C:  *When it doesn’t have, it doesn’t have um um, it doesn’t have an OH*  
  N:  *Aprotic doesn’t bond to an H and protic bonds to an H?*  
  C:  *Yes.* |
### Executing a rule-based equation

**O:** I don’t know what they mean by eleven degrees of unsaturation.

**J:** It’s the formula, right? For that one do you have to figure out from the formula? Or like, the picture?

**E:** Well it gives you the number of C’s, and it has everything else, but it’s like, how many H’s are there? Don’t count them, use the degrees of unsaturation!

**J:** Oh, you just put in like x for it. X for H and then use, since it’s all divided by 2, multiply the 11 by two.

### Symbol-Based Reasoning

#### Manipulating a reaction mechanism

**O:** Oh, okay, that makes sense. I broke a bond, and it has a plus charge. And then from there this is another methyl shift because it’s available. Okay. And then, it will reform to, so, no. So, and then this would get the plus charge when it just stole it, basically, right? And then the Br would come in here to get the final product?

#### Drawing a resonance structure

**G:** So for this first resonance structure, this carbon right here, should have a lone pair on it, right?

**S:** No, on the carbon, and then it has a negative charge too. Because this double bond had to go, and so then the arrows, for his little arrow thing, because doesn’t he want us to draw arrows? It would be one arrow to here, and then this bond, arrow to there. And then it’s going to keep happening. So now the next resonance structure, this arrow’s going to go to here, this guys going to go to here.

### Type of Subject

Students discussed many different topics while working in their study groups. The specific subjects for which we coded included representation, structure, reactions, reactivity, and mechanisms. As students discussed issues of representation, their focus was generally centered on the meaning of a representation. Students might have discussed what a line represented in a line structure (a methyl group), or they might have discussed the methodological rules for drawing mechanism arrows. Similarly, as groups of students worked together to create new representations (such as when they translated a
line structure into a Newman projection), the students discussed issues of representation.

In the following example, students discussed representational issues when creating a name to represent a compound.

\[ O: \text{ Now, because there’s two methyls, I would say 2 comma 8 dimethyl. Neopentyl nonane. } \text{Because the ane goes last.} \]

\[ F: \text{ Yeah. And why’d you put dimethylneopentyl instead of neopentylidimethyl?} \]

\[ O: \text{ Because M comes before N.} \]

\[ F: \text{ Okay.} \]

Structural aspects were discussed by students when they considered (for example) the configuration, conformation, or arrangement of atoms in a molecule. Lewis structures were often discussed in terms of representational aspects (how to draw the structure), but they also elicited discussion about a molecule’s structure. For example, a student may have considered what the charge would be on an atom, or how the atoms might be arranged in space. Conversations about stereochemistry generally corresponded to structural features as well, as was the case in the example below.

\[ A: \text{ So you know there is going to be an E or a Z. But they’re mirror images of each other, so I’m not sure basically which one is which, but you know since they look like that, that it has to be Z. Do you know what I mean? On the top sides for both sides of the double bond? It’s directly connected to a nitrogen, which is directly connected to a carbon. On the bottom, for both sides, it’s directly connected to a carbon, which is directly connected to an oxygen. But since the nitrogen is on the same side, it’s a Z. You know what I mean?} \]

Students also focused on chemical reactions. These reactions represented a process of transformation from starting reagents to final products. When students paid attention to reactions, they focused on the conditions under which a reaction would take place. They focused on circumstances which would lead to product formation, and also
on the chemical changes which came as a result. Thus, the students were likely thinking about the reaction as a whole unit. In the example below, students discussed the particular halogenation reaction and the product that would come as a result.

*L: So the first example is this. Okay, so we’re going to make an alkyne in this one, from an alkene. And we’re going to use Br₂, THF.*

*J: What is that called? What is that reaction called?*

*A: Halogenation.*

*J: So you’re going to have two halogens added on.*

Reactivity, on the other hand, involved consideration of the reactivity of starting compounds and consideration of why chemicals reacted the way in which they did. Thus, when students discussed issues of reactivity, they considered each component in the reaction and how it was related to the whole. In the example below, students discussed reactivity in the context of a particular reaction, but they focused on the conditions which would facilitate a particular reaction.

*A: Won’t this be no reaction? Well, I mean, it’s tertiary.*

*N: It’s S₅¹ E₁. Oh, I think it’s because, well remember, as long as it’s polar,*

*C: It will react slowly*

*A: But it will still react. Because this is polar right? DMF?*

*C: That’s polar, DMF is polar, polar protic. No! It’s polar aprotic.*

*A: But I think as long as it’s polar, it’s okay with it.*

*C: Yes.*

*A: So it’s S₅¹, E₁.*

Finally, students focused on mechanisms. A mechanism is a step-by-step sequence of elementary chemical reactions which reflect an overall process through which compounds may be chemically changed. This code corresponded to students who were discussing either the steps involved in the mechanism, or how to represent those
steps on paper. Although several examples pertaining to mechanisms have already been shown in this appendix, an additional example is shown below:

K: This is a radical reaction like we were talking about today, so when the light hits it
C: So that breaks off
K: This goes here and this goes here
C: And that touches on the carbon
A: And we have to know this?
K: Yeah, he said we needed to know the mechanism for this. This is what he was drawing in class today. You’ll end up with this.

Each of these five subject categories were discussed individually, or in some cases, in conjunction with another subject. That is to say that each subject was not mutually exclusive of another category. For example, if a student was trying to decide whether or not two Lewis structures represented the same compound, they were likely to consider both representational aspects (regarding the Lewis structure) and structural aspects (whether or not the two structures were identical). Similarly, students may have approached a mechanistic task by considering reactivity of the reactant species, or by considering representational aspects involved in drawing the curved arrows. Thus, many study group conversations were coded as pertaining to more than one subject.

Prompt

The last set of codes corresponded to the type of prompt from which students worked. When working in study groups, students worked from either instructor-provided problems, student-created problems, review, or questions. The instructor-provided problems included any problem that was not created by a student. This consisted of problems directly suggested by the instructor (such as homework problems or problems
from a provided practice exam) as well as those indirectly recommended by the instructor. For example, the instructor may have suggested that students work from textbook problems, but the specific problems that students chose may not have been directly attributable to an instructor recommendation. Student-created problems, on the other hand, were those which the students themselves created on the spot and then posed to the rest of their group members. The students who created the problems generally knew the answers themselves and were testing other students to improve their recall ability or to provide teaching examples.

When students reviewed material, there was not a specific problem or task from which they work. Instead, the students may have referenced a list of reactions, or a list of types of stereoisomers, and the students systematically reviewed what products resulted from each reaction, or reviewed what the terms meant. Finally, students also used questions as a prompt for their discussion. In order to be considered a prompt, a question did not pertain directly to any problem or material that was presently being reviewed. Many question prompts appeared to come from students who intentionally brought a list of questions to the study session to have answered.

Each code for a prompt in this study was also given a short descriptive code. For example, if students were reviewing reaction types, the passage of transcript would be coded as “review” but also given the descriptive code “reaction types.” At the end of the coding process, specific types of problems, questions, or methods of review were compared. These descriptive codes were used to compare between different types of
instructor-provided problems and to compare between similar instructor-provided and student-created problems.
APPENDIX C: EXAMPLES OF PROBLEMS THAT REQUIRE DIFFERENT TYPES OF SKILLS

Students might be encouraged to work from different skill-sets if prompted by particular types of problems. This appendix will give examples of problems that could encourage students to use various types of reasoning or different levels of content processing.

Problems that Require Different Types of Reasoning

*Rule-Based Reasoning*

The following set of problems would require students to consider rules that could be applied when discussing organic chemistry concepts:

— Consider the relationship between identical compounds, structural isomers, or resonance structures. What are the defining characteristics (or rules) that can be used to define each set of structures?

— Consider the methodology that you might use to determine whether two chemical compounds are identical, structural isomers, or resonance structures. Describe the step-by-step process that you could use to make this decision.

By requiring a student to list the rules inherent to each type of structure, the student is more apt to consider the defining characteristics of each type of compound. Additionally, by asking students to describe the procedural method of finding the relationship between two structures, the student is asked to consider (or perhaps create) a rule-based process that could be applied in multiple situations. This could help a student
to make conceptual connections between different types of structures and to gain an overall understanding of the distinction between these three relationships.

Case-Based Reasoning

The following problem set is an example of a prompt that could be given to students in order to elicit a case-based approach:

— For the following problem, consider carefully the steps within the halohydrin reaction. If the reaction below took place in absence of water, what further intramolecular reaction could take place that might be similar to the halohydrin reaction?

— What does this tell you about the applicability or limitations of the halohydrin reaction?

— In the reaction below, THF is used as a non-reactive solvent. Give an example of a solvent (besides water) that could have interacted with the intermediate in order to form a different product in a reaction similar to the halohydrin reaction.

\[
\begin{array}{c}
\text{HO} \quad \text{OCH}_3 \\
\text{HO} \quad \text{OCH}_3 \\
\end{array}
\xrightarrow{\text{I}_2 \ \text{THF}}
\begin{array}{c}
\text{HO} \\
\text{OCH}_3 \\
\end{array}
\]

This problem requires students to relate the steps of a reaction that they are presumably familiar with (the halohydrin reaction) to a less familiar reaction in which a carboxylic acid may react in place of water. This type of problem requires a student to consider the applicability and limitations of a particular case. If a student understands the
halohydrin reaction, they should be able to predict the final product of a comparable reaction. They should also be able to propose different solvents (e.g., ethanol) that could result in an analogous reaction. Similarly, other types of problems could elicit case-based reasoning by asking students to consider a particular reaction (or a case of some sort) and requiring them to extend the information to a new set of circumstances.

Model-Based Reasoning

Certain problems may also elicit a model-based approach. The following group of problems provides an example of a task that might encourage students to use model-based reasoning.

— In general, why might a 1,2-hydride shift occur in response to a carbocation formation?

— Use a chemical model to explain why a tertiary carbocation is more readily formed than a secondary carbocation.

— Consider that carbocation formation frequently results in a 1,2-hydride shift. Yet in the following reaction, a hydride shift does not occur (mechanism 1), and instead, an alkyl shift occurs (mechanism 2). What is the driving force of this reaction that results in an alkyl shift rather than a hydride shift?
In response to this prompt, students should be able to use a model-based approach to explain how reactions tend to proceed toward greater enthalpic stabilization. They should recognize that both hyperconjugation and reduced ring strain can lead to the stabilization of a final product. Considering the driving force of a reaction should help students to do more than simply memorize the steps in a reaction, and to carefully consider instead why a reaction might proceed in one way or another.

Problems that Elicit Different Levels of Content Processing

*Remember*

At the “remember” level of content processing, students may be asked to recall some information or define a concept. The following prompt is an example of a question that could be used to help students remember and organize their understanding of the difference between an enantiomer and a diastereomer.

— Describe how an enantiomer would differ from a diastereomer.
Understand

In order to encourage students to understand the meaning of a concept, an instructor could pose a problem such as the one below:

— Zaitsev’s rule states that reactions favor the formation of more stable (more highly substituted) alkenes. Yet reactions that involve bases such as tert-butoxide or LDA will generally result in terminal (less substituted) alkenes. Explain why these particular bases do not follow Zaitsev’s rule.

The above problem requires students to build an explanation based on their understanding of the nature of big, bulky bases. Similar problems that require a student to provide an explanation for some concept would allow an instructor to assess whether or not a student has a clear understanding of the given topic.

Apply

At the level of application, students should be able to apply information to a new set of circumstances. They might do this by applying a well-established set of procedures, or by applying a more general learned principle. In the following example, students are asked to use information regarding the relative stability of carbocations in order to determine the relative rate of reaction steps. They should apply their understanding of carbocation stability in conjunction with their understanding of kinetics in order to answer the problem.
Consider that a tertiary carbocation is generally more energetically stable than a secondary carbocation, which is more stable than a primary carbocation. Given this information, rank the following reaction steps in order of increasing rate of reaction time.

1. $\text{Cl} \rightarrow \text{+}$

2. $\text{Cl} \rightarrow \text{+}$

3. $\text{Cl} \rightarrow \text{+}$

**Analyze**

The “analysis” level of content processing represents one of the higher levels of content processing in which students might participate. In order to encourage students to analyze material, the types of questions that are asked should require students to critically examine the chemistry content that is presented to them. In the following example problem, students would need to compare and analyze two potential mechanisms in order to determine the appropriate mechanistic pathway.

— Consider the reaction shown below. Select the mechanism that best represents the transformation from reactants to products, and explain why the other mechanism is unlikely.
The student solving this problem would need to first analyze the two mechanisms to compare the similarities and differences with one another. The student would also have to recognize that while both mechanisms involve \( S_N2 \) mechanistic steps, only the second mechanism shows proper stereochemistry.

*Create*

At the level of create, students would need to compile information together in order to generate an answer. In the following example problem, students would need to consider the many factors involved in determining whether a reaction would proceed via an elimination or substitution mechanism in order to create an example of an E2 reaction.

— Considering the requirements for a reaction to proceed via the sometimes competing E1, E2, \( S_N1 \) or \( S_N2 \) mechanisms, create an example of a substrate and nucleophile that could react in order to form a primarily E2 product. Indicate what the primary product would be for this reaction.
By using the above example problems as a guideline, instructors might create problem tasks for their students that require varying types of reasoning as well as levels of content processing. When intentionally creating problems that target different skill sets, the instructor can influence more directly the depth of discussion that may result within a peer study group.
APPENDIX D: ADDITIONAL FIGURES

Figure D.1. Average percentages of on-topic words associated with different levels of content processing corresponding to different types of interactions in all of the study groups (as seen in Table 2.3)

Figure D.2. Levels of content processing in study groups as demonstrated across each unit exam (as seen in Table 2.4)
Figure D.3. Discussion prompts and the levels of content processing that corresponded to each type of prompt (as seen in Table 2.5)

a) Instructor Problems
b) Student problems

Figure D.4. Levels of content processing for each of four different types of problems either a) proposed by instructors or b) created by students (as seen in Table 2.6)

Figure D.5. Types of interactions which were generated as a result of different sources of discussion (as seen in Table 2.7)
Figure D.6. Ways in which study groups discussed organic chemistry with respect to five different content focuses (as seen in Table 3.2)

Figure D.7. Types of reasoning that students used in preparation for each exam, reported as a percentage of the words that students spoke in each given study session (as seen in Table 3.3)
Figure D.8. Types of interactions representative of each method of reasoning (as seen in Table 3.5)

Figure D.9. Types of reasoning that students used, corresponding to different cognitive levels of content processing (as seen in Table 3.6)
APPENDIX E: INSTITUTIONAL REVIEW BOARD APPROVAL MATERIALS

Human Subject Approval Letter

21 October 2008

Karen Christian, Graduate Student
Advisor: Vicente Tlanquera, PhD
Chemistry
PO Box 210041

RE: PROJECT NO 08-0801-02 THE USE OF STUDY GROUPS AND THEIR EFFECT ON THE LEARNING PROCESS

Dear Ms. Christian:

We received your research proposal as cited above. The procedures to be followed in this study pose no more than minimal risk to participating subjects and have been reviewed by the Institutional Review Board (IRB) through an Expedited Review procedure as cited in the regulations issued by the U.S. Department of Health and Human Services [45 CFR Part 46.116(b)(1)] based on their inclusion under research categories 5, 6 and 7. As this is not a treatment intervention study, the IRB has waived the statement of Alternative Treatments in the consent form as allowed by 45 CFR 46.116(d)(2). Please make copies of the subject consent form available to your subjects.

Although full Committee review is not required, notification of the study is submitted to the Committee for their endorsement and/or comment, if any, after administrative approval is granted. This project is approved with an expiration date of 20 October 2009.

The Institutional Review Board (IRB) of the University of Arizona has a current Federally Assured of compliance, FWA00004218, which is on file with the Department of Health and Human Services and covers this activity.

Approval is granted with the understanding that no further changes or additions will be made to the procedures followed without the knowledge and approval of the Human Subjects Committee (IRB) and your College or Departmental Review Committee. Any research related physical or psychological harm to any subject must also be reported to each committee.

A university policy requires that all signed subject consent forms be kept in a permanent file in an area designated for that purpose by the Department Head or comparable authority. This will assure their accessibility in the event that university officials require the information and the principal investigator is unavailable for some reason.

Sincerely yours,

Elaine Jones
PhD, RN, FNAP
Chair, Social and Behavioral Sciences Human Subjects Committee

Arizona’s First University – Since 1885
Continuing Review Form

Date: 09/22/10
Investigator: Karen Christians, Graduate Student
Advisor: Vicente Tananqui, PhD
Project No./Title: 08-0801-02 The Use of Study Groups and Their Effect on the Learning Process
Current Period of Approval: 10/21/10 – 10/20/11

IRB Committee Information
IRB2 – IRB00001751
FWA Number: FWA00004218
Expedited Review – Continuing Review

Documents Reviewed Concurrently Status
Continuing Review Report (signed 08/31/10) Appr
VOTF (received 09/02/10) Appr

Determination
Approved as submitted effective 09/22/10

Comments

- Continuing Review Category Status – Data Analysis Only

Regulatory Determination(s)
Criteria for Approval has been met (45 CFR 46.111): The criteria for approval listed in 45 CFR 46.111 have been met (or if previous met, have not changed) in that
Expedite Approval (45 CFR 46.110 Category 5): Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis).
Expedite Approval (45 CFR 46.110 Category 6): Collection of data from voice, video, digital, or image recordings made for research purposes.
Expedite Approval (45 CFR 46.110 Category 7): Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, programs evaluation, human factors evaluation, or quality assurance methodologies.

Elaine Jones
09/22/10
Elaine G. Jones, PhD, RN
Chair, IRB 2 Committee
UA Institutional Review Board

EGI:les

Reminders: Continuing Review materials should be submitted 30-45 days prior to the expiration date to obtain project re-approval
- Projects may be concluded or withdrawn at any time using the forms available at http://orr.u.arizona.edu/irb.
- No changes to a project may be made prior to IRB approval except to eliminate apparent immediate hazard to subjects.
- Original signed consent forms must be stored in the designated departmental location determined by the Department Head.

Arizona’s First University – Since 1885
Form version: 06/18/10
Informed Consent

The use of Study Groups and their Effect on the Learning Process

Introduction
You are being invited to take part in a research study. The information in this form is provided to help you decide whether or not to take part. Study personnel will be available to answer your questions and provide additional information. If you decide to take part in the study, you will be asked to sign this consent form. A copy of this form will be given to you.

What is the purpose of this research study?
You are being invited to participate voluntarily in the above-titled research project. The purpose of this project is to explore how students prepare and study for class. We are interested in the methods and roles that students engage in when participating in a group.

Why are you being asked to participate?
You are being invited because you are currently chemistry student at the undergraduate level.

How many people will be asked to participate in this study?
Approximately 50 people will be asked to participate in this study per year.

What will happen during this study?
If you agree to participate, you will be asked to consent to the following: participate in research activities that involve the use of questionnaires, surveys, interviews, audiotapes, video recording, and/or observations designed to elicit your chemistry knowledge and your chemistry background (teaching, research experiences, schooling, others).

How long will I be in this study?
About two hours of your time will be needed to complete this study.

Are there any risks to me?
The things that you will be doing have no major risks. Although we have tried to avoid risks, you may feel that some questions we ask will be stressful or upsetting. If this occurs you can stop participating immediately.

Are there any benefits to me?
You will not receive any benefit from taking part in this study.

Will there be any costs to me?
Aside from your time, there are no costs for taking part in the study.

Will I be paid to participate in the study?
There will be no monetary compensation for your participation.

Will video or audio recordings be made of me during the study?
We will make an audio or video recording during the study so that we can be certain that your responses are recorded accurately only if you check the appropriate boxes below:

☐ I give my permission for audio and/or video recordings to be made of me during my participation in this study.

☐ I do not give my permission for audio and/or video recordings to be made of me during my participation in this study.

Version: 8/25/09
Page 1 of 2
Participant's Initials____
Will the information that is obtained from me be kept confidential?
The only people who will know that you participated in this study will be the Principal Investigators, Karen Christian and Vicente Talanquer. Your records will be confidential. You will not be identified in any reports or publications resulting from the study. It is possible that representatives of the Federal Government or some other group [Human Subjects Protection Program] that supports the research study will want to come to the University of Arizona to review your information. If that occurs, a copy of the information may be provided to them but your name will be removed before the information is released.

During your participation in this study, your grades will be obtained from Anne Padias, Director of Academic Services in the Chemistry Department, only if you give your permission below:

☐ I give permission for Anne Padias to give you my course grade during my participation in this study.

☐ I do not give my permission for Anne Padias to give you my course grade during my participation in this study.

May I change my mind about participating?
Your participation in this study is voluntary. You may decide to not begin or to stop the study at any time. Your refusing to participate will have no effect on your academic progress. You can discontinue your participation with no effect on your academic progress. Also any new information discovered about the research will be provided to you. This information could affect your willingness to continue your participation.

Whom can I contact for additional information?
You can obtain further information about the research or voice concerns or complaints about the research by calling the Principal Investigator Karen Christian (Ph.D. student) at (520) 620-0980. If you have questions concerning your rights as a research participant, have general questions, concerns or complaints or would like to give input about the research and can’t reach the research team, or want to talk to someone other than the research team, you may call the University of Arizona Human Subjects Protection Program office at (520) 626-8721. (If out of state use the toll-free number 1-866-278-1455.) If you would like to contact the Human Subjects Protection Program by email, please use the following email address http://www.irb.arizona.edu/suggestions.php.

Your Signature
By signing this form, I affirm that I have read the information contained in the form, that the study has been explained to me, that my questions have been answered and that I agree to take part in this study. I do not give up any of my legal rights by signing this form.

Name (Printed)

Participant's Signature Date signed

Statement by person obtaining consent
I certify that I have explained the research study to the person who has agreed to participate, and that he or she has been informed of the purpose, the procedures, the possible risks and potential benefits associated with participation in this study. Any questions raised have been answered to the participant's satisfaction.

Name of study personnel

Study personnel Signature Date signed

Version: 8/25/09 Page 2 of 2 Participant's Initials
APPENDIX F: EXAMPLE STUDY GROUP TRANSCRIPT

This transcript was modified to include only portions of discussion that were on-task and focused on organic chemistry content. Also, discussion pertaining to each practice problem was grouped together for clarity, although in some instances, this represented non-chronological order of the study session (at times, students began another problem and then went back to finish discussing the prior problem). In order to indicate those instances where student discussion may have been interrupted by another conversation, the modified transcript includes the notation *break*. Differentiation between each problem that was worked is indicated by a break in text and a horizontal line across the page.

This transcript comes from study group 13, in preparation for the fourth exam. The length of the observation was 75 minutes, and was made on December 1st, 2009. Three students were present (A, P, and N) and one observer (M).

A: Do you know about going from a fischer to a neuman? Because we’ve seen a couple of those on this test and I don’t think we’ve gone over it.

M: Sure.

A: Do you use the R and S to figure it out?

M: Yeah, if you have trouble going from a fischer to a line structure. Sometimes I just figure out if it’s R or S and then draw the line structure and figure out what it would have to be to be R or S. I might do that for a neuman.

A: Would you just put your fourth priority as a dash then? That way you can figure it out easily?

M: Yeah.

A: Okay. I figured that’s what I would have to do.

M: If you can visualize it, that’s the best, but it can be hard to visualize.

A: Well she just said that the only way to do the fischer is take the fischer, figure out if it’s R or S, draw the line, and then make it your neuman.

P: What test is that?
N: There’s an example when you guys left class or whatever for the review thing. She went over those and it was really helpful. Because I was the only one that asked the questions on it, and she showed all the steps for me so I would understand it.

A: Do you have the notes on it? Okay, well let’s do one. Let’s do one right here.

P: What test is that?

A: This is fall 07.

N: It was have the prediction, and they said, what type of reaction is this, and you had to do it, you know? That’s 1S and E2. And you had to turn a wedge-dash into a neuman and then move the neuman so it’s going to be anti periplanar.

P: Oh, so it’s just. That’s a backside attack, right?

A: You know what a neuman projection is, right?

N: Yeah.

A: Anti periplanar, isn’t that where the biggest things are opposite each other?

N: Um, I honestly have no idea what it means, but if you want to look you can take a look.

A: Let’s just try it the first way real quick.

P: What question is this?

A: So we have an ethyl, one two, this is the carbon, and it has OTs and a methyl.

P: This one sucked!
A: OTs has oxygen in it, right?

P: There’s sulfur . . .

A: Anyway, is this going to be number one then? OTs?

P: Yeah, there’s oxygen. It’s bonded to three oxygens and then a benzene, which that has a metal on it.

A: If it’s got an oxygen on it, that’s what’s attached and that’s going to be number one. So it goes 1,2,3, but that’s sideways, so this is S. Right? That makes sense?

N: Wait, why does the S and R matter?

A: Well then, because then you can figure out which one, and then you can make it a wedge dash over here, and then you can turn it into a neuman.

N: The way she showed us, I mean it, I’m not like saying.

A: Well show me what you’re doing. Use the other marker and do the same thing. That way we can see both ways.

N: It’s just that you don’t have to do S and R for all that.

P: Isn’t that R? 

A: This is on the, the fourth priority is on the side instead of on top, so it’s opposite. So it’s going 1,2,3, it’s going right, but since it’s opposite, it’s S.

N: I’m going to write this over here. I’m not like perfect with this.

A: I just want to know what you learned so I can see both ways and see which way works best for me.
N: Um, so basically, you know how these are always the wedges. These are the wedges and these are the dashes?

A: Right, when you’re looking at it, it’s like upside down.

N: So basically if you were to do the carbons or whatever. (pause while drawing it) Like that, you know? And then you have to do these and these. That’s why you have to do your wedge dash. So if you’re looking at it from this is down, so your eyes are like that you know? Wait, hold on. Then. (slight pause) Fuck. Wait, hold on, can you pass me that binder. Just because I’m not good at this, it’s just the way she said it, it really made sense to me. (pause) Uh, it’s kind of like 3-D thinking. If this goes down and these go up, this is closer to you, you know? (he’s referring to the CH3 and OTs that are coming out of the board)

A: If you’re looking down the ethyl?

N: Yeah, like. Because you have to think that this is at you, and this is facing away from you.

P: But they’re both wedges.

N: This is facing toward you, and this is facing away from you. So it’s like that. You know? And so if this is going down, then you’re kind of like rotating it. I don’t know exactly how to explain it. This is her thing (shows notes to A). She said if you look down on this. And then if you’re looking down at this, this would be closer to you. Maybe I’m not explaining this right, dude. And then this is a wedge.

A: Is it just the left side, is it, is the CH3 a wedge on the other one?

N: Well because this is down I think. But then here, yeah, CH3 would be the wedge. And that’s just because it is what it is, this is the way that she explained it. And then here it would be (writing on the board). Right? But then when you flip that down because this goes like this, these turn. Like that, you know?
P: Ohhhh!

N: We talked about this last time.

P: Isn’t that just like rotating it around the sigma bond?

N: Yeah yeah yeah, exactly. So basically an easy way to remember this is that if the left over here is a wedge or whatever, then this would be. Wait. Did I even say that right? Then this would be the wedge.

P: So it’s then opposites are always the same?

N: Yeah. It’s just flipped.

P: I’m talking in terms of if you were to rotate it, you could get this.

N: Because this is basically this. But to make it nicer, like they want it.

A: Well this carbon is this, right? Right? That’s the same spot there, right?

P: Yeah.

N: Oh, so now you’re doing it a different way. So wait, what?

A: Oh, you did it here’s the methyl. I just drew the ethyl.

N: I don’t know, I just did it sort of the first way.

P: As long as this one and this one are cis, and this one and this one are cis, then you’re fine.
N: Yeah, I think that’s true.

P: It just has to be opposite, so when you look at it. (something) But once these are

A: Are cis?

P: Yeah, of each other.

N: I think that you can do it either way, I think he’s right.

A: Well let’s try it on the second one.

P: Because if you think about it, (something) you can look at this one.

A: Alright, I’m going to draw the second one based off of what we just did and see what I get.

P: I still don’t get how you draw it into the neuman that way though.

A: Once you figure out wedge and dash?

P: No, like. This is what. Eclipsed or gauche? I don’t understand why they put it like that first.
A: Why they put it in gauche?

P: Yeah.

A: I don’t think it would really matter. I don’t know.

P: Okay. That works. (to me) Do you know why this one is eclipsed or gauche looking, and then that one is just stable? Like what are they trying to show? Is that like a mechanism that is not in the instructions?

M: The conformation that is shown for the fischer would be eclipsed. So if these are both coming out, the tosylate and the methyl are eclipsing each other. So this is the exact conformation of this. It’s just that you can rotate it.

P: So in terms, if they wanted you to show it mechanistically, you have to translate it literally the same and then make it the most stable after that?
M: Right, but the one’s that’s important here is the second one. If you can skip this step I don’t think it matters.

P: And then in the instructions it says something about showing a mechanism for it. So I don’t know if they would want us to include that or not.

M: The mechanism would be showing arrows.

P: That’s what I thought, but here it just said. Hmm. It says using the structural formulas and a neuman projection, show the mechanism so you can account for stereo control for each elimination.

A: Wait, what’s going on?

N: It’s a lot like (can’t understand the rest)

P: Like this is the answer box, and there’s a reason why he showed this step, and I’m just trying to figure out why. (pause)

N: Yeah, I’m not. I understand how to move this to a wedge-dash and this to a neuman. But I’m not understanding even what this question is asking.

A: I might just do the R and S.

N: But what’s the question really even asking? Show the mechanism?

P: Yeah, that’s why it’s so weird. I think I can get it, actually. Let me see if I can work it out on my own (all three working individually on answer, long pause) I get it kind of. (long pause)

A: Okay, I got it, doing the R and S.

N: I probably misunderstood it because I didn’t even read the question, I was just trying to find the wedge dash. Does the R/S do something other than find the wedge/dash for that one?

A: The R and S?

N: Yeah.

A: The way you do it with the R and S, is you just put the fourth priority as your dash, that way you know, you can, that’s the easiest way to do an R and S as a line diagram. And then when you draw your neuman, you just envision yourself looking down the bond, and a dash would be going down to the left and that’s a wedge, you go over to the right.
N: I think your way makes more sense, but the way I’m doing it is more, I don’t know.

A: I don’t know either bro bro

N: See like, I got it, but I don’t have this intermediate step right here, and I don’t know what that means.

P: I can tell you how to draw it in a second, I’m just working really slow.

*small break*

N: Do you understand my question? (pause)

P: This is shitty, it’s nothing like I expected. I can get to this part, like I can understand why they got here.

N: Why did they draw it like that? (wondering about first neuman projection) Or is that even an intermediate? Because I got straight to this.

P: Basically what it is, is it shows that basically you’re taking this fischer, and you’re going to look at it like this. Therefore, these two are eclipsed. Eclipsed, eclipsed, eclipsed.

N: What does eclipsed mean?

P: When it’s like this? (showing with hand gestures) When it’s facing like the same. You know when the sun and moon eclipse? Versus, like, gauche? This would be like gauche or

N: So why do they show them eclipsed? Do you even have to show this step, or?

P: Yeah, and that was part of the question. (reading) “Use the structural formulas and neuman projections to show the mechanism so that you can account for the stereocontrol
of each elimination.” So yeah, that was a part of the answer. It was like this, and then you draw. So you’re basically looking at it like this.

N: But I don’t understand. I automatically get this right away. (gets second neuman, not first)

P: Yeah, because what you did, you went through and stabilized it. You put it in the most stable conformation, or the most stable neuman projection. That’s what you’re doing, basically. Which is this. That’s why there’s rotation is involved. But this, you’re literally translating it directly, but just from fischer to neuman.

N: I’m saying like, how from the fischer do you get that these two are closer together?

P: Because you’re looking, you’re taking this, and you’re looking at it like this. So technically the OTs is behind the H.

N: Ohh, oh.

P: OTs is behind the H. OTs behind the methyl. Like you’re looking at it like this. So they took the literal translation and then from here they went about and put it in the most stable.

N: I understand what you mean.

P: You understand? I just don’t know (something)

N: I think what they do is you just have to find this, so I think that, I’m not positive on this, but I’m saying, what if I did the, I don’t even know what it is, but just the wedge dash thing? Instead of that there and then go to that?

P: Well they said use neuman, so.

N: Ohh.

P: Yeah, use structural formulas and neuman projections.

N: Alright, yeah. I don’t know, I don’t understand that first part though. Did you guys do this already yesterday?

A: No, one and a half.

P: Why don’t you wait for us? (he is working ahead of them)

A: Sorry, bro. (long pause)

*break*
A: Alright, NMR! (all working individually for a bit, pause) Integration. (he’s working on the next problem, pause)

A: Sweet. I got the first NMR.

N: His way, NMR is awesome.

A: Oh yeah, it’s way easier than in lab. (long pause, all working individually)

*break*

P: Let’s do this on the board.

A: Sounds good.

P: NMR’s like I’m slowly getting there, and then I rebound, and it’s like, ohh! (pause)

A: So how are those guys? They left streaks on the board. You’re going to draw out the NMR?

P: No, I guess not.

A: It won’t take that long. Okay, so do your first thing. First things first. Count the number of unstaturations.

P: C4H8O2. (pause) So that’s an assumption. Integration is.

A: The number of hydrogens are given in this. The number of hydrogens in each. You’re on the last one, right?

P: First one.

A: I did the measurements earlier. It’s 1.5 to 1 to 1.5, so 3 to 2 to 3.

P: Oh, wow. Wait. Okay. Oh, yeah, I made a simple mistake. Oh! (pause while P writes on the board)

P: (cont’d) Now splitting. (pause) Okay, so let’s theorize. If there’s a triplet, there’s . . . okay. (pause) What does this tell me again? Like splitting?

A: Ethyl.

P: Why? Is it just like a rule?

A: Do you want me to tell you why?

P: Yeah.

A: That’s a, what’s on the NMR?
P: A little over one.

A: Is it 3 2 or 3 from your equation. Which one is the triplet? Is it the 3 the 2 or the 3?

P: Oh. 3.

A: Is it the one farthest to the right?

P: Yeah. Oh no, this is the exact order in relation to this.

A: Okay, that’s what I was asking. That’s a CH3 then, that’s a terminal carbon. And that is a triplet because of the integration. And then it’s got three lines on it, what does that mean?

P: It’s next to three hydrogens.

A: Right. And then go to the fourth line. That’s a quartet. That’s a CH2, right? Which has to be next to what? Something with three hydrogens, right? So that’s your ethyl. CH2CH3. That’s always an ethyl, whenever you see a quartet triplet splitting like that.

P: Okay, so. And now this one’s left.

A: Furthest downfield.

P: No hydrogens.

A: So it’s attached to what? There are only two things it could be attached to.

P: So now it’s which one’s which.

A: That’s what I’m saying. So now you look at chemical shifts.

P: So it can be, it can be like this, or it can be . . . (pause)
A: So which one is it?

P: Umm. (pause) This is the part that I can’t tell which one.

A: It’s the chemical shift. Which one is furthest downfield? And that’s a, what? What is that? So CH3 is attached to the oxygen is what it just told you.

P: Oh, it’s okay.

A: That’s why it’s farthest downfield. Is that the answer? (slight pause)

P: Yep.

A: There you go.

P: Nice. (pause)

N: The integral on these NMRs? They give you that, right? Because the red. Do you have to write that?

P: No, they give you the little stairstep thing or they give you that like, they’ll give you the number of hydrogens with an S or a D or an M.

N: Okay. I got these NMR’s pretty solid. I really like the method that he taught.

P: Which one are you on?

A: I’m working on the last page, I’ll let you catch up to me.

P: Okay, that’s cool. I’m going to go through the NMR’s.

N: I’m doing that too, I’m on the second one right now. Are you on the third?

P: I’m on the second, yeah. Will you wait?
A: I will. (pause as P writes on the board)

![Chemical structure diagram]

P: So, frag. And then.

N: Oh, dude. This is all the same thing? (long pause)

![Chemical structure diagram]

P: Triplet. Those two. (talking to himself as he write on the board)

A: Can I have your charger, P?

P: Yeah, it’s in the front pocket. And then this one is . . . oh! I’m getting quicker with these. Yeah, nice. (long pause)

N: The third one is the one we had to memorize? If there’s six hydrogens?
P: If there’s a multiplet next to six hydrogens, then that’s a doublet, and it’s isopropyl?
A: Uh huh.
N: Fuck, I have to memorize all those.
P: There’s only like four or six rules for that, something like that.
N: That’s not, or yeah, that is a doublet. Isopropyl?
P: Uh huh. One hydrogen multiplet next to a six hydrogen doublet. It can only be that way. So this is . . . (long pause)

P: (cont’d) How do you draw this?
N: Yeah, the third one’s tough.
A: It’s not too bad. The problem is you’re assuming that oxygen is internal.
P: Well I figured out that it’s not, I just drew it.
A: The dead giveaway that there’s a hydrogen all the way over here on 12. It’s a hydrogen directly attached to an oxygen.
P: Yeah, the outside fragments are (something).
N: Wait, can you say that?
A: The fact that the one hydrogen is all the way on twelve, the farthest it can go down, is a dead giveaway that it’s attached to something that is very electronegative, in this case oxygen.

P: The more downfield, like downfield is twelve, right? Upfield is zero?

A: Yeah.

P: So the more down something is, the more polar it is.

A: No, not necessarily. But it is the more likely that it’s attached to something that is polar. These are hydrogens, they’re not polar.

P: Right, yeah yeah yeah.

A: They’re just protons. Alright. So are you ready to do this last page on this one? Because I’m already halfway done with it.

P: No, I’m just trying to figure out this last one and how to put it together.

A: Well, so there’s a hydrogen attached to the oxygen, you know that. So write down your fragments. Now count what you have so far. How many carbons do you have?

P: Six.

A: No, that’s not true. You’re thinking that your carbonyl is three carbons. It’s not. It’s one carbon. That’s just showing that it’s attached, right? It’s just a carbonyl group.

P: So it’s just like that?

A: Yeah, if that’s what helps you remember it.

P: Like in this? 1,2,3, and then this connected would be the four.

A: So there is four. (pause) Now, what’s on the other end though? No. What fragment have you not added yet? You have it under your fragments, that’s your first hint.
N: Oh my god, he has the most confusing answer on here.

P: What, the isopropyl?

A: Yeah, that’s it!

P: Like that?

N: Dude, this answer is ridiculously weird.

A: COOH? That’s just the same thing as that.

N: Oh (laugh) So wait, these two together are an isopropyl? (pointing to splitting on NMR)

A: No. What are you circling right now? Oh yeah, those two, yeah. Whenever you see six hydrogens next to a one hydrogen multiplet, it’s going to be an isopropyl. If you saw nine hydrogens next to a one hydrogen multiplet that would be a t-butyl.

N: Right, but these together, so I don’t have to do an extra CH right here, right?

A: Well there is a carbon attached to that.

N: Right, but these together would be like that.

A: It’s an isopropyl group altogether, yeah.

P: Yeah, you need both.

N: Alright, so number seven?

P: Last one?
N: Oh yeah, it is the last one.

A: When you get to, when you’re done with the t-butyl oxide addition, it’s like the fourth step, let me know, because that’s where I stopped to wait for you guys.

N: Damn, dude.

P: Can we do this on the board?

A: Yeah, do you want me to show you? Remember that peroxide is special when it comes to.
P: Peroxide is anti, or no, I mean its
N: Antimarkovnikov addition.
P: Yeah yeah.
A: So the first step should be pretty easy then.
P: I'm literally just going to (something).
A: It’s cool, I'll just sit here and wait.
N: So magnesium, that would be a grignard? The second one?
A: That would be a Grignard, yeah.
P: “Grignard” (making fun of N’s pronunciation)
N: Fuck you (laugh, long pause while P draws on the board) Is oxygen the leaving group on that?
A: Which one are you talking about?
N: I got, I haven’t really reviewed how to make the grignards or do all of those.
A: Okay, I’ll show you. It’s cool once you get a hang of it. Hey. I’m at the library (on the phone, talking for a bit)
P: Is there a difference between whether they have something above or below the arrow? In terms of whether they’re numbered? Because I know this means that first reaction, and then this one has to come into play later. But I’ve seen it where it’s this or this.
M: That’s the same.
P: Oh, okay. Probably just letting the adderall get to me.
N: Hey, can you explain to me real quick how you do the Grignard?
A: Yeah, come over here. Get a fresh piece of paper. Let’s start with the important details. What makes Grignard so special and the reason why he won the nobel prize for it in 1912. That was on the first test. 1912. The reason it’s so important is because it makes this carbon negative instead of the leaving group, and because of that, the carbon itself can attack. You see what I mean? Because usually the carbocation is positive, and something has to attack it. When you do a Grignard, it makes the carbon negative, and now the carbon can attack stuff. And that’s what makes those special. So basically if you add, just pick something with bromine in it. The dead giveaway for grignard’s too, is a magnesium with a zero on it. Because he’s letting you know that the charge that’s on it is neutral.

P: Is magnesium a metal?

A: Yeah, it’s a neutral metal. It’s had a loss of electrons. So, well I mean you don’t see it on any of the other metals he puts on, just this one. So what happens is, magnesium doesn’t take the bromine out, it just adds itself to bromine. And it gives up two electrons. So bromine has a negative charge, and then carbon has a negative charge. And the one negative, two negative, two positive, it’s all neutral. That’s why when you see it on the test, he’s only going to write it out like this. He won’t show you the charges, you just have to know that this has basically given up two electrons, one to bromine, one to the carbon. So now that you have that, you can add like this. Right? And what happens is the oxygen.

P: That’s all positive, right? (once P is done drawing on the board he comes and listens to A as well)

A: Yeah, that’s all positive. So what happens is this negative right here attacks that positive. And since it’s attacking right there, it has to flatten out the chemical, right? So it actually ends up looking like this. Because it flattens it out and gets rid of the bond. Now usually on a test question when a Grignard is being used

P: I just got lost on why the bond got broken again.

A: The bond got broken when it added to this carbon, because now this carbon doesn’t need two bonds. So the electrons go onto this, and this becomes negative, alright?

P: Oh yeah yeah yeah.

A: So, because it’s in acid, or because it has an extra hydrogen to give up, like in this one, the hydrogen just moves over here and now you have this.

N: So we have this and we want . . . so it’s Br and Mg (mumbling to himself) negative right here

A: (pause) Do you get it now? It makes a little more sense now that you get it done.
N: Wow, see I never learned mechanisms, I just.

P: What’d he do?

A: He just did a Grignard. It’s the second step, but we’re going to have to go over the whole thing.

*break*

P: Alright, next one is the Grignard.

A: We know that the main point of that is to add the number two group.

P: Yeah.

A: I would actually on the test just draw out the mechanism. The mechanism helps me.

N: It makes sense the way you said it.

A: The way it flattens it out and the way that’s why the double bond breaks?

P: Yeah.

A: Okay, so first off just draw what magnesium does, so you get a clear idea. You need to draw the charges out, that will help you. So it’s getting added to that carbon, right? That negative? That’s what’s important here. So. What is the positive charge mostly located on that molecule?

N: In the carbonyl?

A: Right, so that’s where it’s going to attack, right there. Flatten it out. Draw that. Draw the t-way, that’s the easiest way to draw it.

P: Is it always going to be a T?

A: No, usually it’ll bend itself back, but the T helps you see how it actually works. Like he doesn’t have it drawn out as a T in the answer, but.

P: Oh, so it’s got to be.
A: Correct, so where is the oxygen? And that has a charge now, right? Because the double bond is broken and the electrons are donated to the oxygen.

P: So why is this a hydrogen now?

A: That’s the tricky part. The hydrogen will, shit. Okay, so what happened to the hydrogen, is it gets broken into these and goes over to the oxygen.

P: Concerted?

A: I guess so, I mean, that’s what I have it in my notes as.

N: Because it stabilizes the oxygen.

P: So does it look like that? This one random hook?

A: Well that’s the answer.

P: Oh, really? This is right?

N: But no it’s not. You take off that.

A: The carbon is (something). So that’s gone. That arm is gone. It was just a hydrogen, there was no carbon there. The hydrogen went onto the oxygen.

P: So should it be like that?
A: And that’s the answer, yeah.

P: Oh, see! I make a stupid mistake.

N: Dude, everyone makes mistakes.

P: That’s why we’re studying.

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*break*

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P: Okay, so everything in blue is the answer’s.

A: Alright, so let’s do the first one. We’ve got HBr and H2O2 which means antimarkovnikov addition of the bromine. Alright, that’s right.

*break*

P: Wait, is this one too many carbons?
N: No, that’s right.

*break*

N: So the next one, PBr, what’s that called again? What reaction does that form? Is that the heck or no? Heck is boron?

P: I have it over here. Is it the walden inversion?

A: Well it’s not inverting anything, it just adds bromine.

N: It’s the heck I think. Or wait, it’s not!

A: It’s not.

N: I thought all these were (something).

A: It’s just a reaction that adds bromine.

N: Is it?
A: I mean, technically it could be the heck reaction.

N: Well isn’t there a heck catalyst?

A: Well no, yeah, it couldn’t be the heck, because it has to be attached to the carbon.

*break*

A: Okay, you got that. So now, we’re going to add PBr₃.

N: What is the PBr₃ attacking?

A: It’s only going to attack in the spot where anything could leave

N: So the OH?

A: What happens is that. . . does phosphorous make a good base? Is that what happens? With PBr₃? Why does the OH leave basically?

M: The electrons in the oxygen attach to phosphorous as an SN2 reaction, and when that happens bromine leaves.

A: This all happens at once?

M: And then the bromine comes around and attacks the carbon and the oxygen-phosphorous-bromine thing leaves.

A: Oh, so is it kind of like when water attaches. Hold on, let me draw it out.

M: Yeah, like that.

P: Oxonium ion?

A: Yeah. So basically the phosphorous just. Like that?

M: Yeah, the phosphorous will have. . .

A: This is all happening at once, though, right?

M: It will have bromines attached to it.
A: Oh, the PBr3? So the whole thing goes on?

M: It will be PBr2 because when oxygen attaches one of the bromines leave.

A: And then this leaves and this becomes positive?

M: It’s one step I think.

A: Okay, so then this happens and then it goes over to here. It’s like the water one. The water one’s in our notes. Hydronium ion or whatever.

P: It’s oxonium ion, right?

A: Whichever one it’s called. Yeah, right here I see it. It’s under halohydron.

N: So what you’re getting is a bromine instead of an OH basically?

A: Yeah, concerted reaction to put it on the bromine.

P: Is that the whole partial positive charge thing?

A: I don’t think so. I don’t think there are partial positives and things.

P: Oh, okay. I know so many times in my notes I’ve written PBr3. (looking for this in notes)

N: Oh, oh wait. Oh yeah, I did find it. It’s reaction 5, I mean it’s number 5 in your notes, reaction A.

P: The Suzuki?

N: No, it’s not called that.

A: It’s just called 5A. It’s under allylic substitutions.

N: And we’re not supposed to know the mechanism, I guess, because I wrote in my notes, no mechanism until next semester.

P: Can you just give me the date for that? (still trying to find it in his notes)
N: Okay, and then it’s supposed to be an alternative reaction. Oh, it’s the first day, it’s before, I mean it’s the first notes we took, 11/3.

A: Are you going to do the t-butyl guys?

N: It says in my notes it’s an alternative to reaction four, and it’s not in equilibrium, and has no limitations like four has.

P: Oh, right there! (finds it in his notes)

N: So that makes sense.

P: So it’s literally just like swapped?

N: Yeah, and it’s like an improved method or whatever.

P: Okay.

A: We’re good. You want to do the t-butyl oxide?

P: Wait, let me just.

N: And then we know it’s going to be an E reaction. Like, and then E2 is going to work better than 1, so it’s going to be an E2?

P: I didn’t even write down what that one wanted. It says, what mechanism would you expect to observe here? I know the answer because I just saw it. (E2)
N: My TA told me something, and then I heard this at a general review, but there’s two separate things about adding it together. To me it’s like, anytime it’s big thing like that. Can you tell me if I’m saying this wrong? Anytime it’s a big or reactant like that? Like t-butyloxide? Then it’s going to be an elimination always. And then for that. And then I just remember the teacher saying something like, oh, the thing goes to both of them?

P: But they’re both t-butyl, right?

N: And then the teacher said something like, see I don’t know how to tell if it’s E1 or E2, but she said something like E2 always works better?

P: E1 is shit, from what [instructor] says.

N: So I would, just because I know it’s a big one, I know it’s a ready elimination. Just because E2 is the mechanism.

P: I mean that’s the best intuitive guess.

N: Does that make sense or is there a different way to think about it?

P: I think we’re just getting lucky with it, because we’re not into all the technicality of all the little shit yet.

N: Yeah.

P: But for now I think it will work that way.

N: What do you think?

M: Yeah, a big bulky base is always going to be E2.

A: Yeah, you want a big base, which is the next step, the t-butyl oxide in this one.

P: So that, and then this is all from memorizing the nucleophilicity and bases and stuff.
A: I mean, whenever he draws something, and this is from what I’ve noticed so obviously this isn’t set in stone, but whenever he gives us a t-butyl oxide or a tso, it’s because they’re really good at whatever they do. Like OMs is a very good leaving group, OAc very good leaving group, tosylate, very good leaving group. T-butyl oxide, very good base.

P: Okay, but you know that OTs is better than OMs which is better than OAc.

A: Right. Just reverse alphabetical order.

P: Okay, so t-butyl oxide.

A: Is a great base. So what’s it going to do?

P: Leaving group?

A: It’s not on the carbon, it can’t be a leaving group. Oh, do you mean take off the leaving group?

P: Yeah.

A: So to speak.

N: Because it’s an elimination reaction, right?

A: Right. So what happens there though? After that? If it takes off a bromine and a hydrogen, what does it create? Yeah, it takes off a bromine and a hydrogen.

P: So it makes a . . .

A: It’s elimination guys! What happens when you do elimination?

P: Oh! Double bond.

A: There you go! There’s a hydrogen right here. A bromine right here and a hydrogen right here.

P: Oh, yeah.
A: It’s a double bond, so something has to leave.

P: Wow, that’s sad, I didn’t even know a hydrogen was there, but at least I knew it was going to add there.

N: And why would it go there instead of . . .

P: Is this vinyl? Or allylic?

A: It’s the first one. I don’t remember what it’s called. The second one’s vinyl. Or no.

P: Vinyl I think is this guy.

A: Yeah, that’s vinyl.

N: Wait, why? I mean, I thought that at first also, but why doesn’t the double bond go from there to there?

P: It’s less substituted.

N: Okay.


A: Okay, the next one’s tricky. I just looked in my notes.

P: Is it inversion?
A: A radical.

P: Oh, a radical, yeah yeah yeah.

A: And also, when we add NBS, we’re adding bromine. That’s the tricky part. That’s why he wrote tricky. It’s in our notes too. Br is being added. NBS and light. But it’s being added. When it gets added it gets in a weird position, and that’s what’s weird about it. So draw this out without the double bond real quick, right here.

P: But is it when it’s only NBS that there’s also bromine, or does NBS have to do with?

A: The only time we’re going to see this is with NBS and light.

P: Okay.

A: Now, the bromine can either add here or here. But it’s not going to add there, so it’s going to add up here, right? Here’s your bromine. Just draw it out real quick.

P: Here?

A: Yeah. Now what’s radical about it is the double bond. The electrons don’t just disappear. They get moved. And, so where do you think it would go? If it was right here, it can go here, here, or here.
N: Is it inside?

A: Well let’s think.

P: Oh, so is it going to be right here?

A: Just bromine and a double bond, that’s it.

P: God damn it, now I’m!

A: This one’s easier than you think though, because he gives you this. And because this is in here, it helps. There’s going to be no hydrogens here, no hydrogens here, 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15. (counting hydrogens on molecule)

P: Okay, can you show me, because it’s a radical happening?

A: I don’t think he gives us the mechanism for it.

P: There is a mechanism for it. Here it is. Yeah, it’s the first one. (looking in notes, then reading) “Allylic radicals allow for resonance.”

N: And then you pick the better one with zaitsev’s because it’s more stable.

P: That dot above the cyclohexene, that’s a...?

A: It’s an electron.

P: It’s an electron?

A: Yep.

P: See the reason I was going back to, he was like, that can be a wedge hydrogen or whatever. I was like, I know a wedge doesn’t mean anything much.

A: So for the next one we have another E2. We know, we can tell (something). A positive and a negative. So we get something that looks like this. To start with. There’s nothing there.
N: Wait are you guys on the next one now?

P: No, this is the same exact problem.

A: C9H14, so I wonder if this just goes back. I don’t know. So bromine gets eliminated, and that makes sense. Nothing else is being added. So if this was it, let’s count it out and see. What is it? Yeah, it would go here. We have 1,2,3,4,5,6,7,8,9, 1,2,3,4,5,6,7,8,9,10,11,12,13. We have one too many.

P: Do you know what happens here?

M: You decided it’s an E2 reaction.

A: Right, something is being eliminated. Wait, are there two double bonds now?

N: Yeah, there’s two double bonds.

P: Okay, that makes sense!

A: So where does it go? That’s going to say there. Where do you think it will go?

P: That’s what I was thinking, because the potassium would be here, and then you would eliminate that, and then that’s zaitsev’s.
N: I got it, I think.

A: Is this it, N?

N: Uhh. No. Because you can’t have that because the double bond’s there. So you have to, that would be zaitsev now.

A: Yeah, he’s right, because that would have five things around it.

P: Oh, yeah yeah yeah.

N: And that counts out to be the right amount.

A: That makes sense, that was a tricky one. Last one.

P: Ozonolysis!

A: With a zinc metal and acid, so it’s going to cut this.

N: Is it going to cut both?
A: It’s going to cut this one I think.

P: If ozonolysis is involved and there’s two double bonds, does it cut both of them?

A: Yeah, because it wants two answers.

N: No, it does. I think I remember on our last thing, he would show ozonolysis, and it would cut every single one.

P: It cut every one?

N: I think. I mean, that’s what I have in my notes from last time. Because this is from the last test, right?

A: 1,2,3,4,5.

P: And then you have another oxygen.

A: Hold on, I’m trying to think real quick.

P: Yeah, because this. Wait, 1,2,3,4,5. Wait this isn’t, because here it’s going to be. . .

A: There’s not enough carbons on this one.

P: Is this just going to be these?

A: You took it away from me while I was still working on it.

P: Is it just that one that should be C7H10?

A: Hold on, I don’t think they both get split. I think what happens is five, here’s five. Five has six. That’s too many. 1,2,3,4,5,6,7,8. 1,2,3,4,5,6,7. So it loses two carbons somehow. Oh. Is there an equation for this other one? Or a chemical formula?
P: IR 1715 and it’s a strong peak.

A: 1,2,3,4,5,6.

N: Oh shit, I was completely wrong dude. Oh wow. Oh wow! (laughs) Dude.

A: Look at this one though. Try to think of this one. 1,2,3,4,5,6,7,8,9,10, 11,12,13. There should be three oxygens in this one. We suck.

M: I think so.

A: Go ahead. Good grief. Am I right in thinking that this is going to get cut?

M: Uh huh. Is the other one going to be cut?

P: That’s what we don’t know.

A: Well that would mean that there’s 1,2,3,4,5,6,7. That makes sense. So this should be. 1,2,3,4,5,6,7. But there’s two more oxygens on here. But that’s up here, isn’t it? Is that what happens? 1,2,3,4,5,6,7,8,9,10. 1,2,3. 1,2,3,4,5,6. Dang it! I think this might have just messed this up.

N: Wait a minute, I think I got it! Nevermind, I was right, I just wrote it in a weird way.

A: 1,2,3,4,5,6,7. Is that the first one? But no, there would be too many hydrogens, wouldn’t there? 1,2,3,4,5,6,7,8,9,10,11,12. (pause)
N: Yeah, I got it.
A: Do you want to come up here and do it?
N: Yeah, the answer is just in a different. Okay.

P: We need to get an eraser.

N: So, how I did it was I drew that out. This thing out. (pause while writing on board) And then the way I always do these, is I always go, and then when it goes like that, that turns into a linear thing.

P: Oh! I see.

N: And then you go, and so boom boom boom. And then it goes. And then this goes here.

A: And then another double bond oxygen?

P: Hydrogen.

A: And then a hydrogen to the right.

N: Yeah, I always forget those.
A: 1,2,3,4,5,6,7. Perfect. Yeah. Way to go, man! Hot sauce over here!

P: Damn.

N: That was really tough, dude.

A: Are you ready to start the third exam?
REFERENCES


