

ABSTRACT

Title of Dissertation: MAKING SENSE OF 2D DIAGRAMS: EXAMINING HOW MODELS AND MODELING IMPACT NOVICE STUDENTS' DEVELOPMENT OF REPRESENTATIONAL COMPETENCE IN ORGANIC CHEMISTRY

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Diagrams are utilized extensively in chemistry to depict the micromolecular world. Accordingly, success in the discipline is contingent, in part, upon mastering the ability to appropriate, comprehend, and manipulate these representations (Kozma & Russell, 1997). While experts are adept at performing these skills, novices often are not. To remedy this situation and to enhance students' representational competence in the domain, recent research efforts have called for the use of concrete manipulatives as a means to more explicitly illustrate relationships between two-dimensional (2D) diagrams and the three-dimensional (3D) molecules they represent. Such studies have shown, for instance, that students' success at translating between two chemical diagrams improves significantly when they have access to and make effective use of physical models (Stull, Hegarty, Dixon, & Stieff, 2012). Despite advances of this nature, however, exploration of the role of models in alternate learning environments remains a necessity. In addition, further research examining how student and faculty perceptions of modeling in the field influence the choices they make regarding how and why to use models in certain contexts

is essential given the relative dearth of empirical evidence in this area, particularly at the tertiary level.

In this dissertation, I present a series of four studies designed specifically to address these concerns. The first two studies make use of the Representational Translation Task (RTT) assessment developed by Stull and colleagues (2012), as well as an adapted version of the Guay and McDaniel's (1976) *Visualization of Viewpoints* diagnostic (Hegarty, Keehner, Khooshabeh, & Montello, 2009) to examine students' ability to translate between Dash-Wedge, Newman, and Fischer diagrams under various modeling conditions and to explore the degree to which participants' level of spatial aptitude is predictive of success on the RTT. Semi-structured interviews are also conducted to identify potential rationales for why students either elected or did not elect to make use of models on the RTT. Collectively, these studies show that: (a) frequent and effective use of concrete models significantly improves students' performance on the RTT in comparison to students who make limited use of models; (b) when given the choice, students largely elect not to construct their own models for use on the RTT because they find these models too time-consuming to build or because they lack specific instruction on how to build them in the first place; (c) spatial ability is a moderate predictor of success on the RTT, with high spatial ability being especially advantageous when completing challenging items, such as tasks requiring translation to or from a Fischer projection; and (d) removing initial 2D diagrams on the RTT and providing students with access only to 3D concrete models during the tasks led to greater overall performance on the assessment when compared to a control group who only viewed the 2D diagrams.

The third study uses a Likert-item questionnaire, dubbed the My Views of Models (MVM) survey, which is an adapted version of the Student Understanding of Models Survey (SUMS) published by Treagust, Chittleborough, and Mamiala (2002). The purpose of the MVM survey, as its name implies, is to generate a basal account of students' perceptions of models and modeling in Organic Chemistry. Semi-structured interviews are also employed as a means to collect rich and vivid description designed to expand upon students' initial survey responses. This study documents that: (a) students' perceptions of models collectively reflect an intermediary blend of both naïve realist and expert-level views regarding the nature of models and modeling in the field; and (b) students' views are largely framed (and constrained) by their Organic Chemistry classroom experiences, including the type(s) of models they are exposed to in these settings.

The fourth study utilizes a combination of classroom observation and semi-structured interview techniques to explore faculty's perceptions of models and modeling in chemistry and their use(s) of concrete models in the classroom. Results from this study demonstrate that although faculty generally hold positive and nuanced views of models in the field, the ways in which they implement modeling in the classroom during lessons on chemical representations and stereochemistry are often inconsistent with promoting representational competence through the utilization of manipulatives. Faculty were observed, for instance, using student ball-and-stick models in lieu of teaching models that would have been more appropriate given the large lecture format of the course. Likewise, students were not provided with any opportunities during the lesson to

construct models of their own, nor was explicit instruction provided on how they would go about doing so in their own time.

Taken together, these data suggest that concrete models may support students' development of representational competence in the domain, particularly their ability to translate between 2D diagrams. However, significant attention need also be placed on providing students with explicit instruction on how to construct and effectively use these models to accomplish such tasks, as well as sufficient opportunities in which to engage in modeling. Given that most, if not all, of the chemistry-specific modeling experiences students participate in occur in the classroom, understanding both how faculty currently make use of models and how sustained, faculty-centered professional development can support these modeling goals is also of utmost importance.

MAKING SENSE OF 2D DIAGRAMS: EXAMINING HOW MODELS AND
MODELING IMPACT NOVICE STUDENTS' DEVELOPMENT OF
REPRESENTATIONAL COMPETENCE IN ORGANIC CHEMISTRY

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Dedication

This is dedicated to my family:
Jeffrey and Connie Olimpo, my parents
George and Julia Bauer, my adoptive parents
Joy Bauer Olimpo, my wife
and Rocky and Baxter, my “children”

Thank you for sharing this journey with me. You remind me every day to keep my chin up and continue to pursue my dreams. This would not have been possible without you.

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CHAPTER 1: INTRODUCTION

Chemical diagrams are not only part and parcel of the chemical discourse, they constitute a language themselves. To make a rhetorical opposition between words and pictures, text and graphs, does not wash. It is an absurdity. It does not apply to chemical diagrams. (Laszlo, 2011, p. 21)

Chemistry: A Discipline Rich in Representation

Scientific practices have long relied on the use of diagrams and models to further the dissemination and communication of key knowledge to the scientific community. Chemistry, a representation-rich domain, has been no exception. As Laszlo (2011) and others acknowledge, the use of two-dimensional (2D) and three-dimensional (3D) visualizations represent a medium through which chemists describe and explain the micromolecular world and bring that which is intangible to life (Bodner & Domin, 2000; Gilbert, 2005). For this reason, it is perhaps not surprising that success in the discipline is at least partially contingent upon mastering the ability to appropriate, understand, and manipulate these visualizations—skills that later were characterized as constituting an individual's degree of representational competency in the domain (Kozma & Russell, 1997).

The work described here is situated within Kozma and Russell's (1997) broader socio-cognitive theoretical framework of representational competence as it is defined in the context of chemistry and seeks, specifically, to utilize this framework as a lens through which to analyze and describe how novices' competency in the discipline is impacted by the following three factors: *a) novices' use of concrete models to facilitate*

translation between different 2D diagrams in Organic Chemistry; b) novices' perceptions of models and modeling in Organic Chemistry; and c) faculty perceptions of modeling and use of models in the Organic Chemistry classroom. The importance of these factors as critical determinants of student success in chemistry has received growing attention in the chemistry education community over the last decade.

This surge in interest has largely stemmed from empirical evidence suggesting that while experts are adept at employing representational skills to solve visuospatial tasks (VSTs) in the field, novices often are not (Gilbert, 2005). The anecdotal evidence illustrated in the researcher-student conversation below regarding how one should translate between a staggered Dash-Wedge diagram and a Fischer projection further exemplifies this claim and depicts a common reason why students frequently report disliking Organic Chemistry:

Researcher: You're doing a good job, but this [points to a -Cl on the student's Fischer diagram] isn't quite in the right spot. Use the model to help you out!

Student: Why couldn't I just take this substituent [points to a -Cl on the Dash-Wedge diagram] and move it here on the Fischer projection?

Researcher: Remember that the Fischer projection must be in an eclipsed conformation. See, it looks like this [rotates model].

Student: The model doesn't help. Honestly, I just don't get it most of the time.

Why do students “just not get it most of the time”? What makes the study of Organic Chemistry difficult for many students? Historically, the answer to these questions has been credited to many factors, including, most chiefly, lack of experience in Organic Chemistry and/or in solving visuospatial tasks in the field (Pribyl & Bodner, 1987) and low spatial aptitude (Coleman & Gotch, 1998). Using comparative statistical analyses of male and female general chemistry students’ performance on spatial-perceptual items in the *Inventory of Piagetian Development Tasks* (IPDT) assessment, for instance, Coleman and Gotch determined that low spatial ability was associated with lower success in the course. Furthermore, based on longitudinal data over a 12-year period, the authors concluded that spatial ability scores for both males and females were on the decline.

In a large number of cases, the recommendations given for improving students’ representational competency, particularly those students with low spatial ability, have been for students to make greater use of concrete models—which would serve to physically illustrate the spatial nature of the molecules presented in the 2D VSTs—and for faculty to incorporate more models-based instruction into their classroom practice (Molecular Visualization in Science Education Workshop, 2001). However, it is often unclear how students or faculty are to enact these guidelines and recommendations, necessitating that further research be conducted exploring both *who* makes use of such models, under *what* conditions, and *in what ways*. Likewise, based on currently available empirical (Coppola & Jacobs, 2002; Justi & Gilbert, 2001) and anecdotal evidence (such as that cited above) describing student and faculty views of models in chemistry, I argue that we should care not only about how, but also about *why* these individuals elect to use or not to use models when making meaning of 2D diagrams in the field, as this will tell

us a great deal about how students come to see manipulatives as being relevant for developing representational competency in the domain.

Purposes of the Dissertation and Research Questions

Despite more than a decade of research on students' understanding and use of chemical visualizations, relatively few studies have addressed those concerns cited above, including few published study (e.g., Stull et al., 2012) that have examined the role of concrete models as it pertains directly to improving students' ability to translate between 2D diagrams in Organic Chemistry. Additionally, there remains limited empirical evidence examining the potential relationship between tertiary students' use of concrete models, and their performance on translation tasks, to student and faculty perceptions of models and modeling in the field. To address these concerns, the series of studies presented in this dissertation seeks to explore the following central questions:

- 1. How does the type of concrete model students have access to impact their representational competency in Organic Chemistry, particularly their ability to translate between 2D chemical diagrams?**
- 2. In what ways might student and faculty perceptions of models and modeling in Organic Chemistry potentially impact the development of students' representational competency in the domain?**

The first element of this research, addressed in studies one and two, seeks specifically to supplement existing literature describing how concrete models, when

provided to novices pre-built, facilitate students' ability to translate between an initial 2D diagram (shown as a Dash-Wedge, Newman, or Fischer diagram) and a novel, target 2D diagram (Stull et al., 2012). This will be accomplished by exploring variations in the way models are presented to the student. These variations include requiring students to construct their own concrete models for use on representational translation tasks (RTTs), as well as allowing access only to the model and *not* the 2D diagram when solving these tasks. In addition to their application in analyzing how students' success at completing RTTs is affected by the above interventions, these studies will serve to make salient what features of the modeling experience students prefer and how model presentation more broadly impacts students' representational competency in the domain.

While this first objective focuses closely on the cognitive aspects of student learning in the field and the "how" describing students' use of concrete models and interpretation of diagrammatic conventions, it does not explicitly speak to the "why" behind these actions and observations. The second research question, addressed in studies three and four, seeks to speak to this concern by gathering rich and vivid description regarding student and faculty perceptions of models and modeling in Organic Chemistry. While these data will still be constrained by the types of responses participants provide, they will not only build substantially upon existing literature (Bennett, Rollnick, Green, & White, 2001; Dalgety & Coll, 2005; Grosslight, Unger, Jay, & Smith, 1991; Justi & Gilbert, 2002a; Stieff, Scopelitis, Lira, & DeSutter, in preparation; Stull et al., 2012; van Driel & Verloop, 1999), which has at times provided only a cursory examination of the issue, but also more fully begin to explore changes in perception across the novice-expert continuum at the university level rather than at the

secondary level, as has often been the case. Together with studies one and two, these latter studies seek to provide a more holistic account of how novices' develop representational competence in Organic Chemistry by exploring both the cognitive and contextual factors that potentially mediate such competency.

Definitions of Chemistry Terminology

The following terms represent discipline-specific language that will be used throughout the remainder of this dissertation. The definitions for many of these terms are taken directly from McMurry (2008) (textbook Appendix D) and can be found in any standard Organic Chemistry text.

Chiral: A molecule that does not have a plane of symmetry and is therefore not superimposable on its mirror image. The most common cause of chirality in a molecule is the presence of a carbon atom that is bonded to four different substituents.

Substituent: An atom (or group of atoms) substituted in place of hydrogen on the central backbone of a hydrocarbon (a molecule normally consisting entirely of carbon and hydrogen).

Skeletal Structure: A shorthand representation of an organic molecule that illustrates its bonding and some details of its molecular geometry.

Isomer: Molecules that have the same molecular formula but different structures.

Stereoisomer: Isomers that have their atoms connected in the same order but have different three-dimensional arrangements.

Enantiomer: Stereoisomers of a chiral molecule that have a mirror-image relationship. Enantiomers have opposite configurations at all chiral centers (typically, these are carbon centers/atoms).

Diastereomer: Non-mirror-image stereoisomers of a molecule. Diastereomers are stereoisomers that have the same configuration at one or more chiral centers but differ at other chiral centers.

Staggered Conformation: A chemical conformation of a molecule in which substituents on one carbon center are at the maximum distance from substituents on an adjacent carbon center. This requires the torsion angle to be 60° .

Eclipsed Conformation: A chemical conformation of a molecule in which substituents on one carbon center overlay those on an adjacent carbon center. In this case, the torsion angle is 0° .

Model: Except when otherwise indicated (these exceptions occur, mostly, in Chapter 5), my utilization of the terms 'model' and 'modeling' refer to the use of concrete manipulatives. In Chapter 2, unless explicitly stated, it can be assumed the authors are

referring to models as a representation of reality without specific reference to any one type (e.g., scale, mathematical) of model.

Holistic Rotation: The act of rotating, in this case, a model or image in its entirety, rather than making piecemeal, internal rotations.

Sigma-bond Rotation: An internal rotation of bonded atoms about a sigma bond.

CHAPTER 2: LITERATURE REVIEW

I begin this chapter by revisiting the topic of representational competence, which serves as the central focus of this dissertation. I then define and describe the various common forms of visualization used in the field, including their role in promoting representational fluency. Current literature on student and faculty perceptions of chemical visualizations (especially, concrete models) is also discussed with the intent of establishing connections to how novices make use of these visualizations and, therefore, the impact perceptions have on novices' development of representational competence in the domain. Finally, I articulate how a focus on the cognitive and contextual factors influencing students' development of representational competence in Organic Chemistry can be applied as an appropriate conceptual framework for this research.

Representational Competence

In the preceding chapter, I alluded to the importance representational skills and spatial ability have in predicting success in chemistry, specifically in understanding the degree to which novices are successful at translating between 2D diagrams in Organic Chemistry. It is pertinent here to revisit that discussion by identifying the explicit components of representational competence themselves and articulating how these components contribute to individual differences in representational skills in the domain across the novice-expert continuum.

It must be acknowledged first, however, that representational competence is not a construct unique to the field of chemistry. In scientific disciplines, for instance, research

has explored the development of representational competence as it relates to students' understanding of 3D anatomy, students' ability to design representationally-accurate landscapes or terrains, and the impact of reformed physics courses on students' acquisition of representational skills (Azevedo, 2000; Hegarty, Keehner, Cohen, Montello, & Lippa, 2007; Kohl & Finkelstein, 2006). From a more strictly psychological perspective, representational competence has been referred to as the "understanding and utilization of a fundamental rule to the effect that knowledge presented in various forms (e.g., pictures, words, signs) still retains its intrinsic meaning in spite of variations in form of presentation" (Sigel, 1991, p. 189) and has been used broadly as a framework to understand differences in what students know *about* representations, whether it involves school modes of instructed representation or not (diSessa & Sherin, 2000), and children's spontaneous generation and use of multiple forms of representation (Sigel, 1991), among other topics.

With specific regard to my own research, Kozma and Russell (1997), as a result of their work on novices' and experts' use of multiple chemical visualizations when problem-solving in the discipline, contend that representational competence in chemistry is exemplified by the following four characteristics (p. 964):

- The ability to identify and analyze features of a particular representation and patterns of features and use them as evidence to support claims or to explain, draw inferences, and make predictions about relationships among chemical phenomena or concepts

- The ability to transform one representation into another, to map feature of one onto those of another, and to explain the relationship
- The ability to generate or select an appropriate representation or set of representations to explain or warrant claims about relationships among chemical phenomena or concepts
- The ability to explain why a particular representation or set of representations is more appropriate for a particular purpose than alternative representations

Though these skills are requisite for achieving success in the discipline, they are not innate, but rather learned and developed over time. Interestingly, research suggests that much of this learning occurs as a direct result of one's degree of everyday experience dealing with the production, inspection, and use of representations (Yore & Hand, 2010). In the context of chemistry, this observation has led to the development of a stage-like model of representational fluency, proposed by Kozma and Russell (2005), in which individuals advance through five levels of increasing competency in the domain. Based on their earlier experimental work (Kozma & Russell, 1997), the authors suggest that level 1 competency defines individuals who only recognize the surface features of representations (e.g., size and shape of an atom) and who use those features to make sense of novel representations they encounter. Contrastingly, individuals at level 5 competency can seamlessly integrate and translate between different forms of visualization and have a thorough understanding of the conventions and functions of each of these visualizations.

Kozma and Russell's (1997, 2005) work also brought to light several mediating factors that either had the potential to augment or to limit one's degree of representational fluency in the discipline. Chief among these factors was an individual's level of spatial ability. Within the field of Organic Chemistry, Barnea (2000) describes spatial ability as the capacity to "represent, rotate, and invert objects in three dimensions when they are presented in two dimensions"—components he referred to as spatial visualization, spatial orientation, and spatial relations, respectively (as cited in Ferik, Vrtacnik, Blejec, & Gril, 2003; p. 1228). While this definition may be especially pertinent to explaining differences in fluency across the novice-expert continuum, subsequent research has shown that the link between competency and spatial ability is not so clear-cut.

Brownlow and colleagues (2003) report, for instance, that a participant's sex may influence the above relationship, with male Organic Chemistry students outperforming their female counterparts on tests of mental rotation. Qualitative interview data supported this finding, indicating that males felt more competent at solving these mental rotation tasks than females did. This suggests that students' self-efficacy might be a confounding factor worth exploring when drawing inferences about the relationship between spatial ability and success on assessments requiring visuospatial reasoning. Others have challenged these claims, however, arguing that differences in spatial ability disappear when the parameters of the test are altered—such as removing time constraints—and that earlier studies failed to take into account the potential role of alternate factors, such as general intelligence and classroom affordances (such as the availability of models), when predicting success on visuospatial tasks in the domain (Caplan et al., 1985; Stieff et al., 2012).

Likewise, several studies have demonstrated that increased experience solving spatial-representational tasks and greater knowledge of appropriate strategies for successfully doing so may be equally critical determinants of overall representational competency in chemistry. In their quantitative comparison of novice and expert performance on a series of visuospatial problem-solving tasks, for instance, Pribyl and Bodner (1987) noted that expert students tended to draw preliminary representations, though not required by the task, that later helped them in solving each problem. Alternatively, novices were either more likely to have produced nonsymmetrical drawings that misrepresented the spatial arrangement of atoms/molecules in the chemical compound or to have avoided this intermediary step altogether. In a practical sense, these results are interesting, since participants in their sample were all exposed to the same series of problem-solving strategies and, presumably, could therefore make equal and efficient use of them on the assigned tasks.

Regardless of the confounding influence of sex and level of experience, exploration of how spatial ability influences representational competency remains of substantial interest to this field of research, including the studies I discuss herein. This is especially true for two reasons. First, empirical evidence, including preliminary work from our own group, suggests that even novices at the same level of experience in the domain exhibit widely varying degrees of spatial ability (Olimpo & Dixon, 2012a; Stull et al., 2012), predicating that success not only on specific problem-solving tasks but in the domain overall may be influenced, at least in some regard, by spatial aptitude. This observation will be explored in further depth throughout elements of this dissertation.

Second, it appears evident that spatial ability also greatly influences the types of strategies novices employ when problem-solving in chemistry. In addition to the diagrammatic strategy discussed by Pribyl and Bodner (1987), use of 3D concrete and virtual models has emerged as a viable approach designed to support students' understanding of chemical phenomena, especially students with low spatial ability. This has been found to be true when virtual models are integrated into existent curricula, such as Wu and Shah's (2004) implementation of a toxicology unit in which students could manipulate chemical compounds to simulate hypothetical toxic interactions, as well as when concrete models are used in quasi-experimental settings (Stull et al., 2012).

Specifically, using quantitative methods, Stull and colleagues (2012) showed that students who had access to concrete models aligned to match the initial 2D diagram presented on a representational translation task were significantly more successful at translating between the two, 2D diagrams of a molecule than their peers who did not have access to models. This finding is of particular importance because it suggests that the presence of models might help novices achieve greater levels of representational competency than predicted by Kozma and Russell's (2005) stage-like construct, at least in the context described. However, one would expect this to be true only if students saw value in using models, even if uniquely for the purposes of problem-solving, and/or were exposed to models in the classroom learning environment or in their everyday experiences (e.g., laboratory research).

For this reason, it is noteworthy also to consider student and faculty perceptions of models and modeling in chemistry, as well as the use(s) of models in the Organic Chemistry classroom. Treagust and Chittleborough (2001) assert that many chemistry

courses “fail to show the relevance, usefulness, and applicability of chemistry to everyday life” (p. 243). The types of representation used in science courses and in science textbooks do little to prevent this outcome (Kozma, 2003; Kumi & Dixon, in preparation; Kumi, Olimpo, Bartlett, & Dixon, 2013), and student interest in chemistry often mirrors their perception of the degree to which the teacher is invested in the subject (Dalgety & Coll, 2005; Treagust, Chittleborough, & Mamiala, 2004).

Furthermore, when juxtaposed with students’ ability to translate between representations, studies show that novices’ use of models tends to be constrained by the structure of the learning environment itself. Using open-ended student survey response data, Stieff and colleagues (in preparation) and Stull and colleagues (2012) both illustrated, for instance, that students self-reported not using models on translation tasks because they were not allowed to use them on in-class assessments, had received no formal instruction on how to use models, and/or found models too time-consuming to construct. These perceptions and attitudes, though often remaining unspoken, are salient features shaping students’ representational competency in the domain as well.

Representations and Representational Translation in Organic Chemistry

In order to be able to discuss the practical uses of visualizations in chemistry and their link to representational competence, a brief review of the most commonly used forms of representation is necessary. While concrete models have gained much traction in the chemistry classroom over the last decade, research suggests that the 2D diagram, which depicts a two-dimensional structure either virtually or on paper, remains the most prevalent form of visualization in the field (Bodner & Domin, 2000).

Instructional practices in Organic Chemistry have typically relied on three different diagrammatic representations, namely: 1) Dash-Wedge diagrams; 2) Newman projections; and 3) Fischer projections. Each of these diagrams affords the user unique advantages, particularly when considering aspects of molecular structure and stereochemistry. In the Dash-Wedge convention (Figure 1a), for instance, the chemical bonds linking each atom within a molecule are commonly illustrated either as a solid line, wedge, or dashed line. The bonds that are solid lines are within the plane of the page, the dash formalism indicates bonds going into the plane of the page, and the wedge indicates bonds that are coming out of the plane of the page. For this reason, the Dash-Wedge diagram is suggested to provide the user with the greatest degree of 3D information about the molecule in comparison to the other 2D diagrams that will subsequently be discussed (McMurry, 2008).

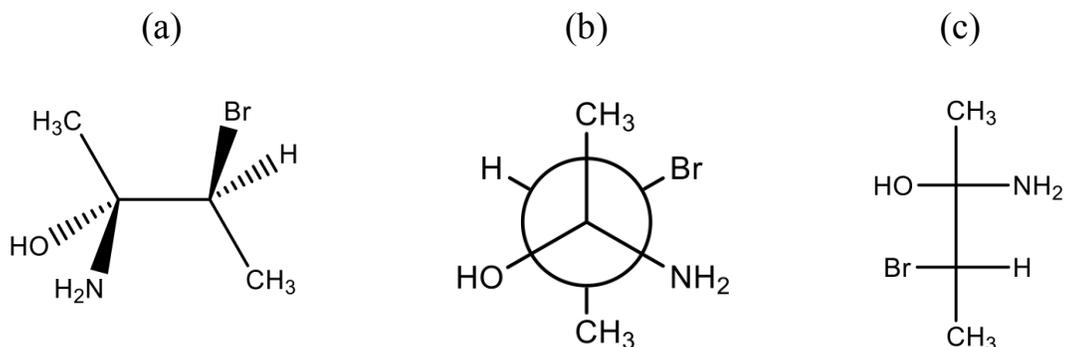


Figure 1. Common 2D representations in chemistry. (a) Dash-Wedge diagram; (b) Newman projection; (c) Fischer projection.

Similarly, the Newman projection (Figure 1b) offers the viewer an opportunity to more readily visualize the spatial relationships between chemical groups (e.g., -Br, -

CH₃, -OH above) on adjacent carbons, as it provides an end-on view of the entire molecule. For this reason, Newman projections are frequently used to determine the lowest-energy, or most stable, conformation of a molecule (Newman, 1955). According to standard convention, the circle represents the space between the two carbon atoms that form the bond the person is looking down, and the substituents on the front and back carbon are placed around the circle. Much like the Dash-Wedge representation, the Newman projection precludes that the spatial arrangement of atoms and molecules within the compound is dependent upon the specific bonds linking these groups and the relative position (i.e., bond angle) of these bonds with respect to the entire compound.

The same cannot be said, however, for the Fischer projection, which fails to capture any three-dimensional information regarding the molecule or compound itself (Figure 2c). An affordance of this caveat is that the Fischer projection allows one to assign spatial arrangements for a given carbon within the molecule with relative ease (McMurry, 2008). Diagrammatically, substituents within the molecule are arranged on opposing ends of either horizontal or vertical bonds, which project toward and away from the viewer, respectively. Due to the nature of the representation itself, and resultant from Fischer's own professional interests, the Fischer projection is most frequently used in Organic Chemistry and Biochemistry courses to depict carbohydrates (Robyt, 1998).

Throughout their study of Organic Chemistry, novices are frequently required to translate between these three different diagrams. Research suggests that students employ a host of strategies for doing so and that, generally, these fall into either analytic or imagistic techniques (Stieff, 2011; Stieff & Raje, 2010). In one study detailing differences in novice and expert use of problem-solving approaches when completing

translation tasks, Stieff and Raje (2010) show, for instance, that students might elect to perform an imagistic strategy to solve a Dash-Wedge to Newman translation task by creating a mental model of the Dash-Wedge diagram and then envisioning it rotating, holistically, to adopt the conformation of a Newman projection, all the while maintaining proper spatial positioning of substituents in the molecule.

This approach, though utilized frequently by novices, is highly error-prone for two reasons. First, it requires students to cognitively grapple both with chemistry content and with spatial manipulation simultaneously (Bethell-Fox & Shepard, 1988). Secondly, if the molecule has to undergo a conformational change (i.e., staggered versus eclipsed), as is the case in a comparison of Figures 1a and 1b versus 1c above, additional mental manipulation is required, further complicating the task.

Alternatively, taking the same example of translating from a Dash-Wedge to Newman diagram, students employing an analytic strategy might first draw the template for the Newman projection and then transpose substituents on the left side of the Dash-Wedge diagram to the front face of the Newman, preserving spatial orientation. Finally, substituents on the right side of the Dash-Wedge diagram would be transposed to the back face of the Newman, again preserving spatial orientation, completing the task (Stieff & Raje, 2010). Importantly, this strategy, like the imagistic technique previously described, is only successful if students *accurately* preserve the spatial order of substituents when transposing from one representation to the other, which can be difficult. Furthermore, the technique can be fallible if students inappropriately apply the strategy, such as “flattening” the Dash-Wedge to form a Fischer projection (Kumi &

Dixon, in preparation; Kumi et al., 2013) because they fail to remember that the Fischer must be in an eclipsed conformation.

Concrete and Virtual Models: Tools for Promoting Representational Competency in Chemistry

Given the numerous complexities inherent of 2D diagrams found in the field, models have become increasingly valued in the chemistry classroom. Research suggests that this is because allowing students to manipulate and work with models supports and helps to increase their understanding of core chemical concepts, such as stereochemistry and molecular structure, as well as potentially reduces the misconceptions students develop about chemical phenomena (Stull et al., 2012; Treagust & Chittleborough, 2001). From a pedagogical standpoint, models-based instruction also adheres more closely to constructivist modes of teaching, in which students' prior knowledge and experiences are an inherent, and valued, part of the learning context (Kozma, 2003; Schank & Kozma, 2002; Treagust et al., 2004).

Schank and Kozma's (2002) research involving the *ChemSense Knowledge Building Environment* (CKBE) is one such example of constructivist practices in action. The study, which adopted a mixed methods approach to analyze 67 high school and first-year college students' misconceptions of matter, chemical processes, and chemical systems, revealed significant improvement in students' representational competence post-intervention, as well as increased detailed discussion about chemical reactions and phenomena. The authors attributed observed learning gains and collaborative growth to CKBE's increased opportunities for students and faculty to partner in data collection and

construction of physical and virtual models designed to illustrate chemical phenomena, as well as the provision of a context in which to engage in discourse aimed at explaining the mechanisms behind why these phenomena occur.

One traditionally used concrete manipulative in both Schank and Kozma's (2002) work and throughout the domain is the ball-and-stick model (Figure 2). Conventionally, the balls each represent a particular atom or substituent—white for Hydrogen, red for Oxygen, black for Carbon, etc.—while the sticks represent the bonds between these atoms.

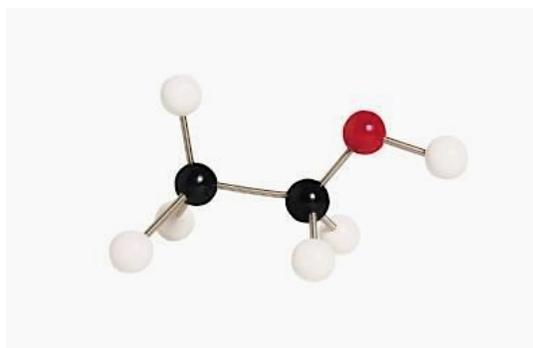


Figure 2. Ball-and-stick model.

In addition to the benefits discussed previously, research suggests that students find concrete models to be valuable because they are physical entities that can be rotated and manipulated (Olimpo, Kunin, & Dixon, unpublished). Ongoing work from our own group, in which first-semester Organic Chemistry students participated in either individual or focus group interviews designed to ascertain their perceptions of models and modeling in chemistry, revealed that some students also felt these models alleviated the need to mentally imagine the 2D diagrams in three dimensions altogether (Olimpo & Dixon, 2012b; Stull et al., 2012). Furthermore, Stull and colleagues (2012) have shown

through statistical analysis that student success at translating between 2D chemical representations increases when students have access to and make use of concrete models when problem-solving, particularly when these models are aligned to match the initial, 2D diagram.

More recently, as educators and administrators alike continue to place increasing value on the role of technology in promoting instructional practices and student learning, the media through which visuospatial and representational tasks are presented has witnessed a marked shift toward virtual molecular modeling interfaces. Though my dissertation does not focus on virtual models (this is being explored by my collaborators; see Stull, Barrett, & Hegarty, 2013), it is still important to note that such instruments have received great acclaim due to their general pervasiveness and the flexibility they offer in conveying knowledge (Liminiou, Roberts, & Papadopoulos, 2008). However, given the emergent nature of these technologies, it is imperative to consider the effectiveness of these resources, both individually and in conjunction with current pedagogical practices, to enhance students' representational competence in the domain.

In illustrating the importance of embedding molecular visualization tools within existent curricula, Wu and colleagues (2000, 2001) note that incorporation of their eChem software package during a standard unit on toxins greatly increased students' ability to visualize the chemical composition of the toxins studied and easily allowed for students to manipulate chemical conditions given novel hypothetical situations (e.g., areas of high toxin concentration vs. areas of low concentration). The eChem tool (Figure 3), the authors claim, accomplishes these criteria given its ability to convert between micro- and macroscopic representations, its ability to display multiple

representations such as ball-and-stick and wire-frame simultaneously, and its user-friendly interface.

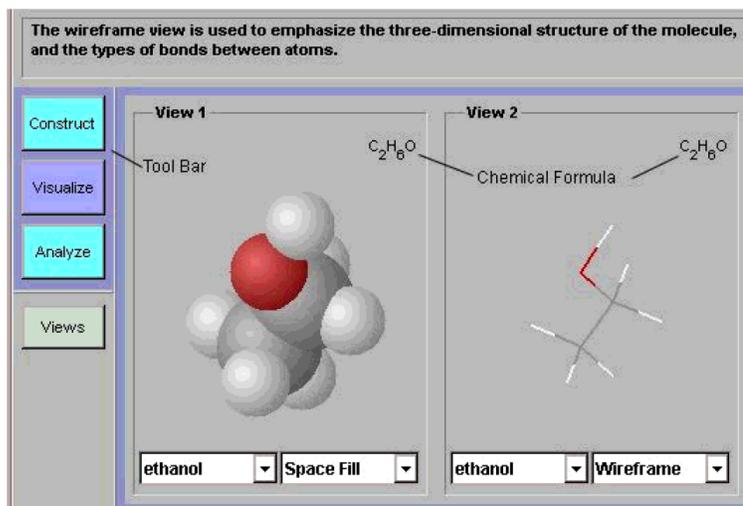


Figure 3. eChem graphical interface (reproduced with permission from Wu, Krajcik, & Soloway, 2001).

Furthermore, the authors generally advocate for the use of technology in the classroom as a critical means for linking visualization and conceptual understanding—a connection they feel is imperative for student success in chemistry.

Despite the benefits offered by such tools, however, the true value of virtual molecular modeling programs remains clouded by the fact that few empirical studies have investigated the use of computer-based modeling instruments as a primary means of instruction (diSessa & Sherin, 2000; Yore & Hand, 2010). The diversity of chemical modeling programs available (e.g., Chem 3-D, Chime) also precludes that future studies need take into consideration which programmatic aspects of virtual models are most effectual, particularly in the eyes of chemistry students and faculty. In this way, future

technologies can reliably build off their predecessors to expand the representational possibilities available to students.

In addition, it is important to remember that models, whether physical or virtual in nature, are anthropogenic creations designed to convey sub-microscopic information through a macroscopic lens. As such, the phenomenon being represented by the model is largely context- and purpose-driven. Research has illustrated that students, particularly novices, often hold “incomplete” views of models due to a lack of experience or understanding of how the representation fits into that broader context (Coll, 2006). This is an area of concern that must be addressed when incorporating models-based instruction into one’s teaching repertoire.

Grosslight, Unger, Jay, and Smith (1991), in their *in vivo* analysis of the role of models in chemistry teaching, applied a descriptive interpretive approach to examine this need. The authors contend that many of the misconceptions students derive from modeling tasks are linked directly to the assumptions they make about the model itself. “Novices tend to think of models in concrete terms, meaning that students and novices think of models as scale models of reality – the ball or sphere used in teaching is exactly like an atom – apart from its size,” they state (as cited in Coll, 2006; p. 67). Furthermore, students often fail to understand that models often build upon other models, causing them to overlook the interactions present between chemical molecules and compounds and leading them to perceive that representational tasks in the field are “difficult” or without value. In this regard, placing models into authentic contexts and providing students with an opportunity to construct and manipulate these models may result in improvement in

students' representational skills and their understanding of the nature of chemical interactions (Prins, Bulte, van Driel, & Pilot, 2009).

Students' perceptions that representational items are entirely factual also lead them to experience trouble in translating between representational systems (e.g., from Fischer diagram to Newman diagram to 3D model) – a skill that is crucial for success in Organic Chemistry. In a review focusing on the role of representations in problem-solving, Bodner and Domin (2000) reflect on informal interviews they conducted with more than 200 undergraduate and graduate students designed to explore the degree to which these individuals successfully made use of visualizations across general and Organic Chemistry courses. The authors note that the majority of students exhibited difficulty in recognizing multiple representations of the *same* molecule, largely due to an overemphasis on one type of molecular representation versus another during instruction, and that they claimed that tasks requiring use of multiple representations were not “fair” (p. 26). This finding has potentially severe implications for students seeking to become experts in the field, particularly for those students who do not seek assistance in correcting their misconceptions or who are not enrolled in courses where the value of manipulatives is stressed.

In discussing student misconceptions, it is important to clarify that the fault does not rest entirely on the student. In some instances, the nature of the concrete molecular model (or representation) itself can unknowingly perpetuate misconceptions. The ball-and-stick model, for example, though utilized widely in the field, mixes elements of spatial realism and graphical conventions that are typically uncommon or opaque to

novices (Molecular Visualization in Science Education Workshop, 2001). The balls and sticks themselves have few, if any, properties of the chemical symbols they represent.

Student Perceptions of Models and Modeling in Organic Chemistry

While the research discussed herein is not intended or designed to focus exclusively on students' misconceptions of chemical visualizations, the above findings suggest that it is appropriate to more broadly explore and analyze novice and expert perceptions of representations, models, and modeling in chemistry, as this may tell us (the educational community) a significant amount about how these individuals come to understand and make use of those visualizations. Adapting from Markic and Eilks' (2008) research on first-year German chemistry teachers perceptions of teaching and learning in the domain, I define perceptions as *all views, attitudes, and beliefs that teachers and students hold in their minds, which influence, to a certain extent, their (potential) behavior as teachers or students within their subject*. Specifically, the research I present here focuses only on those perceptions pertaining to the ways in which students and faculty "see" and define models (especially, but not limited to, concrete models) as functionally relevant to solving representational translation tasks in the context of Organic Chemistry and the broader role(s) models have in conveying and communicating scientific knowledge in the field, both in the classroom and at the bench. Such perceptions might include, for instance, the uses of visualizations by experts in the field and the relationship(s) between diagrams and concrete models, among other topics.

While there appears to be limited empirical research in this specific area, several studies have demonstrated that individuals' perceptions of molecules and molecular

representations as a whole change dramatically as they gain expertise in the field (Kozma & Russell, 2005; Treagust & Chittleborough, 2001). As I have alluded to above, and as is evidenced in Kozma and Russell's (2005) work on novices' use of multiple representations when solving visuospatial tasks in chemistry, neophytes attend largely to the surface features of diagrams and representations—the placement of substituents on a molecule, the size of the molecule itself, the color of substituents on a concrete model—with little understanding of the underlying structure or functional value of that representation or model. This invariably leads students to perceive these visualizations as being exact replicas of the phenomenon they intend to represent, what Grosslight and colleagues (1991) termed a naïve realist epistemology of visualizations. Presumably, this occurs for two reasons. First, novices often acquire and negotiate the purposes and meaning of visualizations simultaneously. This is due to an immediate need for the use of these visualizations, particularly in demonstrating mastery of academic content on formal assessments in chemistry courses (Schwartz, Rogat, Meritt, & Krajcik, 2007).

Secondly, students are routinely presented with multi-representational displays, whether in the classroom, in textbooks, or online, and tend to default to visualizations which are familiar to them. Hinze and colleagues (unpublished) show, for instance, that when asked to choose between a ball-and-stick model and an electron potential map (EPM) to solve a given task, novices consistently rely on the ball-and-stick models regardless of whether or not the EPM is actually more applicable to the task at hand. The authors suggested that this observation was due to students perceiving the ball-and-stick models as being most relevant to problem-solving. However, this inference could potentially be problematic, as a) it is highly likely that students would simply avoid

EPMs because they are unfamiliar, regardless of their relevance to the task; and b) students may not see any functional value in EPMS either because they do not possess enough detail about what they are or because they do not understand how they are used in real-world contexts. This latter concern is evidenced in textbooks as well, which often present chemical visualizations as static, unquestionable facts disconnected from the authentic contexts in which they exist and are used (De Jong, van Driel, & Verloop, 2005).

As students advance in their study of chemistry, however, significant conceptual and epistemological shifts occur in their views of visualizations that begin to approximate those held by experts in the field. This shift is evidenced in one study by Treagust and Chittleborough (2001), in which the authors administered a paper-and-pencil questionnaire to 250 8th to 11th grade students that was designed to gain insight into these students' perceptions of the roles of models in science. The authors discovered that "students [gain] a better understanding of the role of models as they learn more about science" and that this encompasses a better understanding of "the role of models in science with respect to the representational nature of models, the changing nature of models, and the multiplicity of models" (<http://www.waier.org.au/forums/2001/treagust.html>). In other words, students are not only increasingly aware that models exist for specific purposes but that multiple types of models can be used to depict chemical entities or events.

Nevertheless, this assertion is predicated upon the fact that students *do* receive an opportunity to engage with these forms of visualization and that, presumably, they develop an interest in how models and representations are used to describe chemical

phenomena. Treagust and Chittleborough's (2001) claim, as it stands, is also very general. At what point in their academic career do students come to exhibit these shifts, and what factors, specifically, lead to a deeper understanding of the role of models in chemistry? In fact, Treagust, Chittleborough, and Mamiala (2004) later contend that only a small percentage of students, even those who have taken a number of chemistry courses, identify that visualizations can be used to test ideas, make predictions, and solve a variety of problems in the domain when asked about these items on surveys and in interviews. From these findings, it is evident that this is certainly a concern worth exploring in further detail.

Faculty Perceptions of Models and Modeling in Organic Chemistry

It is important to remember also that the transition from novice to advanced student is mediated by a number of factors, most principally interaction with faculty. For this reason, I argue that it is further necessary to consider not only *what* views faculty hold of chemical visualizations, but also a) *how* faculty perceptions of chemical visualizations impact the learning process and b) how these perceptions become transparent in the classroom. In this way, we can begin to draw tacit links between these beliefs and actions and how they might influence the manner in which students subsequently come to comprehend and view representations and models in the field, ultimately having the potential to greatly shape student success and learning in the discipline.

It is perhaps not surprising that research collectively suggests that experts hold more sophisticated views of chemical representations and models than do students (van

Driel & Verloop, 1999). In a study in which 71 experienced high-school teachers were asked to complete a Likert-item questionnaire and interview regarding their knowledge of models and modeling across scientific disciplines, for instance, van Driel and Verloop (1999) show that these instructors, including a subset of faculty in chemistry, felt visualizations could be predictive and inexact, especially when modeling abstract entities or processes—a view not commonly held by novices. This finding was later corroborated by several subsequent studies in the field, which demonstrated that faculty believed building models required creativity and intuition, particularly when dealing with the intangible world (Bailer-Jones, 2002; Justi & Gilbert, 2002a), and that it was not necessary (or sufficient) to rely on only one form of visualization alone to explain a given phenomenon.

In addition, experts are cognizant of the relationships existent between various forms of visualization, such as 2D diagrams and 3D models, and the appropriate use of these visualizations in the field. Empirical work suggests that part of the reason why experts come to hold such nuanced views of chemical representations and models may be due to the extensive experience they have working with visualizations across varying settings. In their ethnographic study of how community-derived representational systems and activities support the work of chemists in laboratory settings, Kozma and colleagues (2000) observe, for example, that representations are highly pervasive in the laboratory, with molecular structures drawn on whiteboards, formulae and symbols on flasks and test tubes, and reactions written in laboratory notebooks. The authors go on to show that the conversations occurring in the laboratory revolve around these visualizations, such as a principle investigator demonstrating to graduate students how a ball-and-stick model

might be used to understand the 3D spatial information of a molecule, highlighting the communicative nature they have in the field. The unanswered question that remains, then, is how do we, as educators, encourage novice students to see these same connections, understanding that their experiences are likely not as diverse as our own or of more advanced students in the field?

The answer to this question is somewhat paradoxical. While the above findings suggest that faculty possess sufficient content knowledge and enthusiasm regarding models and the use of visualizations in the field and in educational contexts, it is uncertain whether they are capable of leading students to develop this same understanding and practice *through teaching*. In fact, as a result of conducting interviews with seven Dutch science teachers about the role of models in teaching, van Driel (1998) finds that “despite the fact that some teachers declared themselves in favour of the use of teaching strategies focused on the nature of models and/or modeling activities by their students, their practice did not reflect this commitment. In practice they place great[er] importance on learning the content of specific scientific/historical models” (as cited in Justi & Gilbert, 2002b; p. 1276). Though this study did not focus exclusively on faculty in academia, it indicates that the role visualizations have in helping students learn about science may be obfuscated or deemphasized in the classroom.

This conjecture is supported by work from Justi and Gilbert (2001) who, in a similar study, explored Brazilian science teachers’ use of models at the primary, secondary, and university level. These authors discovered that while teachers generally were aware of the value of using models in classroom settings, there were an ‘alarmingly high’ number of teachers who did not pay attention to students’ ideas about models and

the use of these models, as well as a “discrepancy between teachers’ attitudes towards modeling as an important educational activity, and their sparse use of modeling in classroom practice” (as cited in van Driel & Verloop, 2002; p. 1256). While a powerful statement of how instructors incorporate models-based practices into their classrooms, this latter finding, in particular, implies that greater attention need be placed on exploring *why* such a discrepancy exists in the first place, as this has severe implications for *how* such a discrepancy might impact the manner in which students come to understand and work with visualizations in chemistry contexts, as discussed above.

Research suggests that the answer to this concern may lie partially in the fact that faculty, especially novice instructors, often tend to take decisions regarding model use in the classroom for granted – not necessarily because they believe there is no instructional value to using models and other forms of visualization but because they are mirroring the didactic experiences they themselves encountered in the classroom, in which consideration of these issues was downplayed or irrelevant (Coppola & Jacobs, 2002). Coll (2006), in his review of the literature on model use in chemistry teaching, contends that, overall, this leads to favoring of more heuristic approaches to solving visuospatial tasks in the domain or to fixation on a single, “best” model that is believed to be appropriate for a given task. For some faculty, this also leads to a perception that certain visualizations, such as ball-and-stick models, are only useful in specific situations, such as when conducting experiments, though this is certainly not the case (Boz & Uzuntiryaki, 2006). Regardless, it is little wonder, then, that students may adopt a similar view if these are the experiences they encounter daily in the classroom.

From a practical standpoint, research also proposes that a viable solution to improving the quality of models-based instruction and, therefore, student and faculty perceptions of visualizations in chemistry, may be accomplished by having faculty align classroom instruction with constructivist principles of teaching and learning (Koballa, Gräber, Coleman, & Kemp, 2000). Such principles would presumably accommodate students' prior knowledge and engage students in exploring, first-hand, how visualizations can be utilized to solve visuospatial tasks in the field. Treagust, Chittleborough, and Mamiala (2002) report that structuring classroom instruction in this manner is particularly important as “model-based reasoning is [currently] not practiced in school science, and, consequently, students have no experience with models being used in scientific ways” (p. 365). While this may be an overgeneralization, it certainly echoes the call for action and change that is so prominent across the work in this field.

Indeed, I have acknowledged above that this constructivist mindset is contradictory to conceptualizations of teaching as “knowledge transfer” and science learning as “intake of knowledge” (Koballa et al., 2000; Yerrick, Parke, & Nugent, 1997), both views that continue to permeate chemistry learning environments. To encourage faculty use of visualizations and, therefore hopefully, students use of these tools, reports from the Molecular Visualization in Science Education Workshop (2001) propose that “instructional materials for visualization [should] be easy for instructors to learn and use. Faculty need guidance and support when beginning to use molecular visualization in teaching. Workshops...on the research and dissemination of new ideas [are also needed]” (p. 16). Such recommendations are a positive step in motivating

discourse around these important issues. However, there are three potential concerns regarding this agenda that must be kept in mind.

First, guidance alone is arguably not sufficient to promote constructivist views of teaching and learning in the discipline as they relate to use of visualizations. In fact, it cannot be assumed that a learning environment is constructivist simply because it is labeled as such. Research suggests that individuals hold strikingly different views of what constitutes “constructivist” teaching and learning, ranging from beliefs that constructivism is meant to actively engage students in the learning process to beliefs that constructivism is anything aside from didactic instruction (Saunders & Goldenberg, 1996; Wheatly, 1991). As a result, even those instructors claiming to subscribe to a constructivist philosophy will likely use visualizations in diverse and inconsistent ways. Far worse, however, is that teachers remaining firm to non-constructivist views will likely assimilate guided strategies into their transmissionist approach, ultimately resulting in visualizations being used in non-constructivist ways in the classroom. This, in turn, may potentially create a negative portrayal of these representations and models that will be transmitted to and influence students’ perceptions of these visualizations (Dalgety & Coll, 2005; Treagust et al., 2004).

Second, in conjunction with the latter argument above, while students may *report* having a better understanding of visualizations and how these tools can be integrated into their learning process as a result of engaging in the use of these visualizations in the classroom, research shows that they still often hold surface-level views of visualizations and adopt superficial (i.e., non-models based) learning strategies when approaching visuospatial tasks in the domain (Chang, 2005; Grosslight et al., 1991). This may be

because they see visualizations, specifically models, as “just another ‘thing’” to complicate what is already occurring in the classroom instead of as meaning-making tools with a purpose. Exploring this possibility, and its broader implications for student learning and success on visuospatial tasks, is a necessity.

Lastly, it is important to remember that a large percentage of faculty engaged in teaching in the discipline are not formal members of the chemistry education community. Therefore, they may simply be less aware of the literature describing the affordances models may have in supporting students’ understanding of 2D representations in Organic Chemistry. In addition, because Organic Chemistry is traditionally a large enrollment, introductory course in which it has become common practice to “[hold] large didactic lectures followed by cookbook laboratories...[leaving] little room for doing anything but moving predigested information from textbooks to testing” (Coppola & Jacobs, 2002), the combination of these factors may present as insurmountable barriers to faculty who might otherwise be interested in using models-based practices in the classroom, whether they are aware of these potential barriers or not.

Examining Representational Competence: A Conceptual Framework

It is undeniable that representational skills and other visuospatial problem-solving strategies, as Kozma and Russell (1997) define them, are cognitive in nature. The later development of a stage-like model of representational competency (Kozma & Russell, 2005) likewise suggests that certain cognitive barriers exist that prevent novices from directly achieving representational fluency in chemistry, at least until they have come to comprehend the complexities of a particular visualization beyond a superficial level.

While this may be the case, I have argued that understanding *how* and *why* novices come to be increasingly representationally competent, particularly in their ability to make use of concrete models to translate between 2D diagrams in Organic Chemistry, warrants examination of the social contexts in which these novices are exposed to and engage with such manipulatives.

This proposed framework, in its broadest sense, is best described by Hawkins (1974) in his piece entitled *I, thou, it, The informed vision*. In this work, Hawkins argues that it is not only imperative to consider the interactions occurring between students and faculty and the personal views, actions, and thought-processes of these individuals, but also the content (i.e., the physical artifacts) around which these actions occur and the larger context in which these interactions are taking place. In regard to my own research, this framework looks as follows (Figure 4):

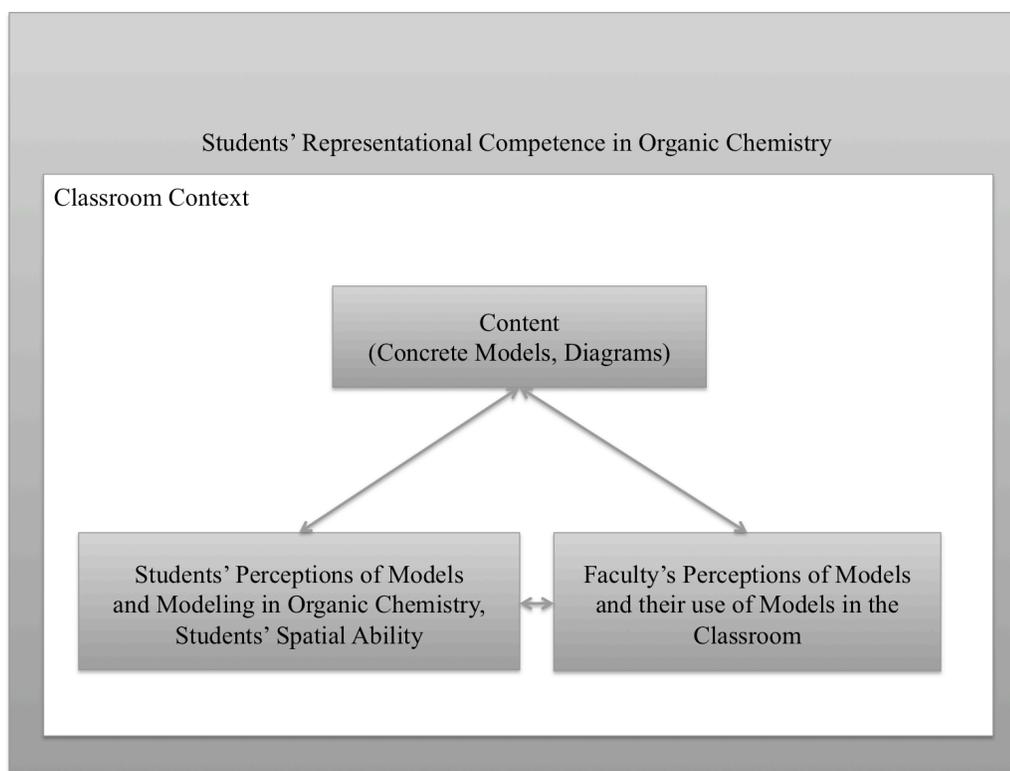


Figure 4. Conceptual Framework

This framework embodies the earlier described notion that students' representational competence (again, particularly representational translation ability) in Organic Chemistry is potentially impacted by a number of factors, including their own beliefs about and use(s) of models, the classroom context in which they are taught about 2D representations and afforded the opportunity to use concrete manipulatives to understand 2D-3D molecular relationships, and faculty's views of models and modeling. This framework also assigns equal importance to each of these factors and, similar in purpose to Hawkins' work, acknowledges that developing a holistic account of how students come to be representationally competent in the domain is contingent upon close examination of all of these features. While this is the case, and while students may find value in using models to solve representational translation tasks, this framework does *not*

preclude that such manipulatives are at the epicenter of improving students' representational competence in the domain nor that they are necessarily more efficient than other strategies students employ to solve representational translation tasks. Gray and Fu's (2004) soft constraints hypothesis acknowledges, in fact, that substituting external actions (such as model manipulation) for internal processes is not always easier or more straightforward.

It is important to note also that both cognitive and socio-situative theories of representational competence have been previously described in the literature (Kozma, 2003; Kozma et al., 2000), and, therefore, my choice to make use of a blended version of these frameworks is not an unusual one. In his review of experimental and naturalistic studies regarding the role of representations in understanding science, for instance, Kozma (2003) illustrates how a cognitive-situative lens can be used to explore individuals' views of and approaches to using multiple forms of representation (such as concrete models and diagrams) as well as the contextual factors influencing these processes. The author reports that while "scientists coordinate features within and across representations to reason about their research and negotiate shared understanding based on underlying entities and processes...students have difficulty moving across or connecting multiple representations" (p. 205). If, as Kozma argues, these representations have multiple cognitive and social affordances for experts, and our goal is to advance novices' understanding of these visualizations to expert-level, then it stands to reason that a framework which focuses both on the cognitive *and* the contextual is an appropriate lens for analyzing how students develop representational competence in the domain of Organic Chemistry.

CHAPTER 3: RESEARCH METHODOLOGY

The ability to appropriate, interpret, and manipulate representations is essential for success in Organic Chemistry. In an effort to examine how students' use of and perceptions regarding models impact their representational competency in the domain, this corpus of research adopts a mixed methods approach—one combining elements of at least one quantitative and one qualitative tradition (Driscoll, Appiah-Yeboah, Salib, & Rupert, 2007; Onwuegbuzie & Johnson, 2004). This same approach is applied to the analysis of faculty perceptions of models and their modeling practices in the classroom, allowing for critical student-faculty-content linkages to be established and examined (Hawkins, 1974) and, ultimately, a more holistic account of how Organic Chemistry instruction influences students' representational skills in the discipline to be ascertained. Specific methods to address this goal are detailed below.

Rationale for Conducting a Mixed Methods Study

The selection of an appropriate research methodology and consideration of the techniques that stem from that methodological umbrella are critical when designing any research agenda. Creswell (2008) contends that this choice is often enveloped within broader epistemological and theoretical commitments that reflect the researcher's stance on how knowledge is generated and viewed, as well as what type(s) of data the researcher considers to be appropriate for addressing his research questions or hypotheses. Despite the complexity with which such methodological decisions must be reached, however, decades of educational research have been conducted under the auspice that only two

paradigmatic approaches to conducting research exist. These two approaches are, of course, quantitative and qualitative modes of inquiry.

Quantitative methodologies, as described by Bryman (1984), have traditionally been depicted as being positivist or empiricist in nature, concerned most fundamentally with “operational definitions, objectivity, replicability, causality, and the like” (p. 77). To meet these ideals, quantitative researchers obtain data from large sample populations and subject these data to rigorous statistical analyses designed to provide evidence either for or against their research hypotheses. Data can be collected using a variety of instruments—such as surveys, questionnaires, or diagnostic assessments—and results can often be generalized to similar populations pending that the initial participants in the study constituted a representative sample (Coll & Chapman, 2000; Jacobs, Kawanaka, & Stigler, 1999).

Contrastingly, qualitative research is seen as being more subjective in nature. Unlike the positivist or empiricist viewpoint, qualitative methodologies are concerned with observing participants and understanding how they interact with and make meaning of their environment (Bryman, 1984). The methods employed by qualitative researchers are therefore more diverse, including discourse analysis, interviews, and observations, and are believed to be more appropriate for inquiry in the social sciences (Hammersley, 2002). Furthermore, whereas quantitative methodologies focus on describing relationships in large populations, qualitative approaches are lauded for their ability to provide detailed and rich description of a smaller number of cases or participants. This affordance is particularly beneficial, as it ensures that the nuances and unanticipated

occurrences that take place within that smaller cohort can be extensively examined (Coll & Chapman, 2000; Jacobs et al., 1999).

While this is the case, two criticisms of this attribute are that it potentially allows for the introduction of researcher bias and that it reduces the external validity of the study (Guba & Lincoln, 1989). To rectify these concerns, Coll and Chapman (2000) propose that qualitative researchers attend to the following four criteria:

- *Credibility*, which is concerned with isomorphism between constructed realities, and which is enhanced by prolonged engagement, persistent observation, and member checking
- *Dependability*, which is concerned with the stability of data over time; namely, that methodological changes are fully documented and described
- *Confirmability*, which seeks to rule out investigator bias by making findings available to the public (i.e., research community) for scrutiny
- *Transferability*, the degree to which the results of the study are actually transferable, or generalizable, to novel contexts

Together, these criteria are designed to add rigor to one's study in ways comparable to quantitative research and are suitable and adaptable to all forms of qualitative inquiry.

Though presented as a dichotomy thus far, it has become increasingly evident in the field that quantitative and qualitative approaches possess complementary, non-overlapping strengths and weaknesses (Creswell, 2008; Hammersley, 2002; Smith & Heshusius, 1986). Coll and Chapman (2000) go so far as to suggest that “qualitative and

quantitative approaches are investigating the same thing, and the difference is essentially one of choice of data tools” (p. 3). This line of reasoning has led to the development of a mixed methods approach to inquiry.

Onwuegbuzie and Johnson (2004) suggest that the strength of mixed methods research is that the combination of verbal and numerical data adds a degree of meaning and precision not achieved by either source alone. Furthermore, a broader range of research questions can be addressed because the researcher is not limited to a single method or approach. The tradeoff to this is that mixed methods research is often more time-consuming and expensive than either qualitative or quantitative research alone given added demands of data collection and analysis. In addition, the mixed methods researcher must be well-versed in each method he is using and understand how these methods complement one another (Onwuegbuzie & Johnson, 2004).

The series of studies described herein follows in the mixed methods tradition and employs a partially-mixed, concurrent, dominant-status mixed methods research design (Leech & Onwuegbuzie, 2009). The terms “partially-mixed” and “dominant-status” indicate, in this case, that significantly greater emphasis is being placed on quantitative methods, though both quantitative and qualitative approaches will be applied with regard to data analysis and interpretation. Finally, the design is concurrent because the quantitative and qualitative studies detailed in the following section will occur roughly within the same time interval.

For practical purposes, it is important to note also that mixed methods research has been adopted as the major methodological paradigm by several previous studies throughout the field and so is not an atypical choice of study design in this instance. For

example, in an effort to understand how students made use of a general chemistry web-based learning tutorial, Donovan and Nakhleh (2001) administered a survey containing both scaled-response and open-ended prompts. As a follow up, the authors also conducted several interviews with students. These data were then subjected to either quantitative or qualitative analyses, as appropriate, which demonstrated that students perceived the tutorial to be more informative and beneficial to their learning than standard lecture-based content delivery formats traditionally employed in general chemistry courses.

Similarly, Herrington and Nakhleh (2003) employed a survey-based, mixed methods approach to explore what perspectives teaching assistants and undergraduates held about how effective chemistry laboratory instruction should be defined. Scaled items were subjected to statistical analyses, while free-response items on the survey were carefully explained and articulated using a descriptive interpretive approach. The authors argued that this dual approach allowed for complementation between participants' Likert-item responses and their more explicit rationale for selecting these responses.

With specific regard to my own research, however, the choice to use a mixed methods design is rather novel. I say this not to suggest that previous empirical work on the use of visualizations in chemistry education has somehow fallen behind the times, but rather to point out that these studies have traditionally subscribed to one of two philosophies. First, several studies, including some of those reviewed above, focus almost exclusively either on student learning and success in chemistry or on student and, to a lesser degree, faculty perceptions of some element of teaching and learning in the domain (see, as examples, Stull et al., 2012; van Driel & Verloop, 1999). This practice is

not to be viewed negatively, as both themes are not always the expressed objective of the research study. However, it is often the case, accordingly, that these studies make almost exclusive use of either quantitative or qualitative approaches to inquiry, respectively.

Similarly, while the author(s) may report using a mixed methods approach, unequal weight is given to one research element or the other, yielding a bias toward predominantly quantitative or qualitative methods and analyses. For instance, Stull and colleagues (2012) conducted a quasi-experimental study in which students were encouraged to make use of physical manipulatives to solve representational translation tasks and were then asked, via open-ended survey prompts, to explain why they elected or did not elect to use the manipulatives provided when problem-solving. Though themes in student survey responses were subsequently obtained using a grounded theory approach, students' responses were ultimately tabulated in a quantitative format and presented alongside performance data, which itself was analyzed using statistical methods. In this case, scant attention was placed on interpreting student survey data qualitatively, which limited the contextual lens through which to make meaning of these data.

The studies I describe below acknowledge these current concerns in the field and seek to build upon earlier work by establishing connections between the *how* and *why* of students' use of concrete models to solve representational translation tasks in Organic Chemistry. While quantitative methods will indeed be used to analyze student performance on these tasks as well as interpret student survey data, qualitative analysis of interview and classroom observation data will help to provide rich description and expansion of observed outcomes. In this way, as Leech and Onwuegbuzie (2009) rightly

asserted, the quantitative and qualitative traditions will complement one another, allowing for a more holistic account of how students engage with chemistry visualizations in Organic Chemistry to be obtained.

Study 1: A Comparative Account of Students Use of Pre-Constructed versus *de novo* Construction of Concrete Models on Representational Translation Tasks (RTTs)

The use of pre-constructed concrete models has been shown to dramatically increase students' success at translating between Dash-Wedge, Newman, and Fischer diagrams with the stipulation that students use these manipulatives in a purposeful manner to complete translation tasks (Stull et al., 2012). In this study, I employ the following methods to assess how student success on RTTs is influenced, in particular, by availability only of a modeling kit, not pre-constructed models, requiring students to build models *ab initio* should they wish to use them on the assessment.

Participant sampling and treatment allocation procedures. Participants (n = 108) were randomly selected from all current Organic Chemistry I students at Andrews University¹. Upon consent, participants were then randomly assigned to one of three treatment conditions: a) No Model, in which the individual did not have access to concrete models; b) Pre-Built Model, in which a pre-constructed concrete model aligned to match the initial 2D diagram in the RTT was made available; and c) Model Building, in which students had access to a modeling kit throughout the duration of the RTT assessment. It is important to note that while all participants had received prior

¹ A pseudonym. Any relation to real-life universities bearing this name is purely coincidental.

instruction on Dash-Wedge, Newman, and Fischer diagrams, none had received instruction regarding how to construct or utilize concrete models for the purpose of translating between these representations, though such models were used routinely in the Organic Chemistry I courses in which these students were enrolled. Participants received course credit for their participation in the study, as approved by the university's Institutional Review Board (IRB).

Representational Translation Task (RTT) assessment. The three types of representations used in this assessment include the Dash-Wedge, Newman, and Fischer diagrams, examples of which are illustrated in Figure 1. Though participants were familiar with these representations from their classroom experiences, a brief (~1 page) description and depiction of each of these diagrams was presented to participants prior to administering the assessment, the nature of which is described below. This practice was intended to ensure that all participants were reminded of the names and conventions of these diagrams.

The representational translation tasks found in the assessment itself required participants to translate one initial diagram of a molecule to a different target diagram of the same molecule. The initial and target diagrams always differed (i.e., participants were not asked, for instance, to translate a staggered Newman projection to an eclipsed Newman projection), as this more closely approximated the degree of cognitive complexity inherent of similar tasks completed by experts in the field. Each problem was presented on a sheet of 8.5" x 11" paper with the initial diagram presented in the center of the page and specific instructions indicating the desired target representation printed at

the top of the page. For those individuals in the Pre-Built (Aligned) and Model Building conditions, a sentence was inserted at the bottom of the page reminding participants that they could make use of the models provided if they felt it would benefit them during the tasks. Though encouraged to do so, participants were not required to use models on any of the assessment items.

Nine different straight chain molecules were each presented twice, creating 18 unique tasks, three representing each translation type (Newman to Dash-Wedge, Fischer to Dash-Wedge, Newman to Fischer, and vice versa). These problems are presented in Appendix A. In an effort to reduce data biasing, students were required to complete the tasks in sequential order and were not allowed to return to any previously completed items. The assessment itself was untimed.

As noted previously, participants in the modeling treatment conditions received either pre-constructed concrete models or modeling kits for use during the exercise. These models (see figure 2, as example) were constructed using the HGS Introductory Organic Chemistry/1000 molecular modeling kit available from Hinomoto Plastics Co., LTD. This kit is similar to the modeling kit available for purchase in the university bookstore and is frequently used in college chemistry courses.

Spatial ability diagnostic. An adapted version of the Guay and McDaniels (1976) *Visualization of Viewpoints* test (Hegarty et al., 2007) was used as a measure of spatial ability and perspective taking. This test was selected because of its emphasis on mental rotation – one strategy commonly employed by individuals to solve the types of representational translation tasks used in my study. The assessment presents participants

with two images, one containing an object presented in the center of a cube (represented on paper in two dimensions) and the other a target figure that is a rotated form of the object presented in the first panel. The participant is asked to identify the corner of the cube that serves as the vantage point for observing the object as it is shown in the rotated panel. The diagnostic consists of 24 items administered in one, 8-minute block, with each item being worth one point (Appendix B).

Semi-structured interviews. Following completion of the RTT, participants were asked to respond to one open-ended interview prompt, namely: “can you please briefly explain why you chose [not] to use concrete models during this assessment.” This prompt was intended to provide baseline data on the potential reasons driving participants’ observed modeling behaviors and the nature of these reasons (e.g., negative perceptions of models, low self-efficacy beliefs). Because the interviews adopted a semi-structured format (Drever, 1995), the length of interviews ranged from one to four minutes in length.

Study administration procedure. All participants were tested individually. Participants provided informed consent prior to completing the spatial ability diagnostic and the RTT, each of which is described above. In addition, participants were videotaped during the course of the study with their permission. These videos were made available only to research team personnel. Videodata were later used to code participants’ behavioral actions (e.g., reconfiguring or building models, gesturing) during the tasks. A copy of the video coding protocol for this study can be found in Appendix C. Participant

responses to the open-ended interview prompt were analyzed using a descriptive interpretive approach (Smith, Harré, & van Langenhove, 1995) to discern common thematic elements and patterns in the data.

Summary of quantitative analysis. Participant responses on the RTT assessment were coded either as correct or incorrect, where accuracy equated to correct placement of substituents on correct chiral centers on the molecule. Incorrect responses were further coded by the type of error made (e.g., enantiomer, diastereomer), and error frequencies tabulated for each translation type. Both a raw composite score, as well as sub-scores for each translation type were computed. Mean differences in raw performance between treatment groups were assessed using a one-way ANOVA procedure, with treatment condition as the independent variable and raw score as the dependent variable. Mean differences in raw performance between model users (model use on 50% or more of translation tasks) and non-users (model use on <50% of translation tasks) were also assessed using an independent t-test protocol.

Sub-score analyses were conducted using a repeated-measures ANOVA procedure with Lower-Bound correction, with treatment condition serving as the independent variable and aggregated sub-scores for Dash-Wedge to Newman (and vice versa), Newman to Fischer (and vice versa), and Dash-Wedge to Fischer (and vice versa) tasks serving as three unique dependent variables. Given previous reports indicating variable levels of student performance on translation tasks involving Fischer Projections vs. Dash-Wedge and Newman diagrams (Stull et al., 2012), this latter analysis was expected to be particularly informative. All items were coded by myself and one other

rater, and a kappa statistic was calculated to determine inter-rater reliability. Differences in scoring were resolved by a third rater with expertise in the fields of chemistry and chemistry education.

Scores on the spatial ability diagnostic were calculated as previously described and entered directly into SPSS (IBM®) for use in linear regression analyses. Videodata were coded by myself and one other rater, and a kappa statistic was calculated to determine inter-rater reliability. Behavior frequencies were then determined using SPSS, and these frequencies were subsequently used in both descriptive and linear regression analyses to examine potential relationships between behaviors and success on RTT items.

Study 2: Examining Students' Use of Concrete Models in the absence of 2D

Diagrams

While current research in the field has examined students' success at translating between representations when concrete models are presented in conjunction with 2D diagrams (Kozma & Russell, 1997; Stull et al., 2012), little to no evidence appears available to address how students' representational competency is impacted in 3D-only conditions (i.e., when diagrams are not initially present for observation).

Participant sampling and treatment allocation procedures. Participants (n = 60) were randomly selected from all current Organic Chemistry I students at Andrews University. Upon consent, participants were then randomly assigned to one of two treatment conditions: a) 2D-only, in which the individual did not have access to concrete models; or b) 3D-only, in which a pre-constructed concrete model aligned to match the

initial 2D diagram in the RTT was made available, though the 2D diagram itself was not presented to the participant. All participants in this study had received prior instruction on Dash-Wedge, Newman, and Fischer diagrams. None of the participants in the 3D-only condition had received instruction regarding how to construct or utilize concrete models for the purpose of translating between these representations, though they were exposed to such models extensively in their Organic Chemistry I course. Participants received course credit for their participation in the study, as approved by the university's Institutional Review Board (IRB).

Representational Translation Task (RTT) assessment. All participants completed the RTT assessment, as described in study one above. The RTT protocol utilized for participants in the 2D-only treatment group was identical to that of the No Model participant protocol discussed previously and illustrated in Appendix A. For participants in the 3D-only treatment condition, a modified protocol was utilized. Specifically, initial 2D diagrams were removed from the 18 problem sheets presented in the RTT assessment, and participants were instead informed that the 3D concrete models provided to them for each problem were aligned to match the initial representation indicated in the task (Figure 5). The 18 problems included in the RTT assessment across both treatment conditions were otherwise identical.

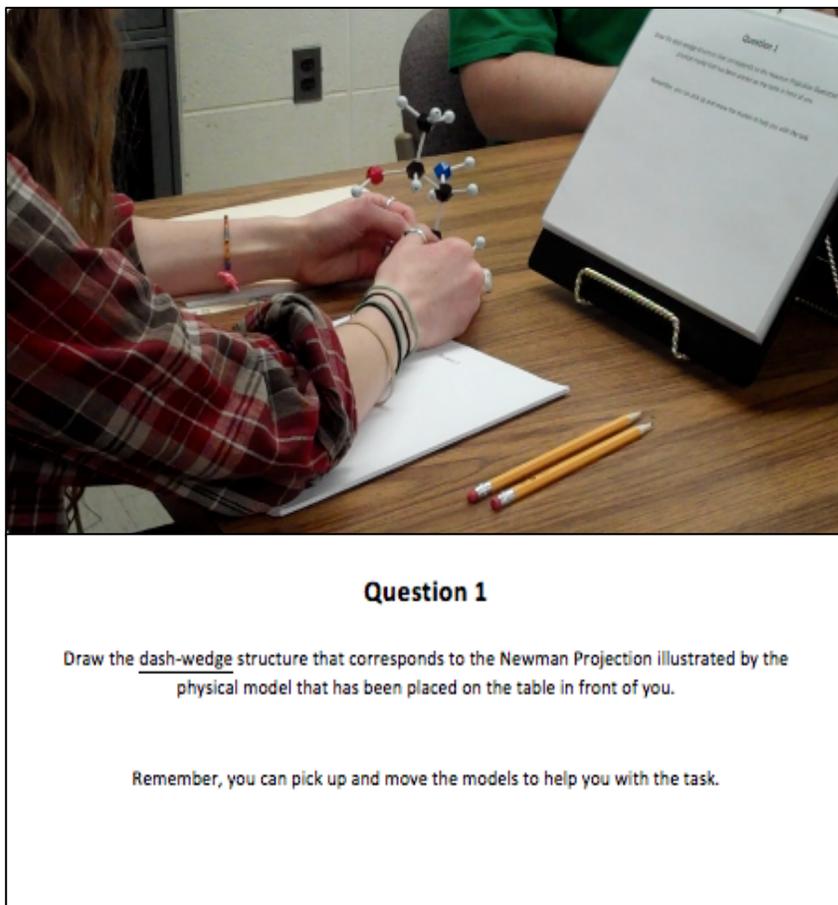


Figure 5. Sample RTT item and experimental setup for 3D-only treatment condition.

Spatial ability diagnostic. All participants completed the adapted version of the Guay and McDaniels (1976) *Visualization of Viewpoints* test (Hegarty et al., 2007), as described in study one above.

Semi-structured interviews. Following completion of the RTT, participants were asked to respond to a series of open-ended interview prompts. These prompts are presented in Appendix D. The intent of conducting these semi-structured interviews was identical to that described in study one above. Specifically, participants' responses to

these prompts were intended to provide baseline data on the potential reasons driving their observed modeling behaviors and the nature of these reasons (e.g., negative perceptions of models, low self-efficacy beliefs). Because the interviews adopted a semi-structured format (Drever, 1995), the length of interviews ranged from two to five minutes in length.

Study administration procedure. Procedures for this experiment were identical to those presented in study one with the exception that a modified video-coding scheme was used. This protocol can be found in Appendix E.

Summary of quantitative analysis. Quantitative analyses were conducted as described in study one; however, analyses of the errors students made on translation tasks and sub-score analyses of performance on specific translation types were not conducted as extensively given that the focus of this study was similar to that of the first study (and therefore it was anticipated that the trends in error and sub-score data would be nearly congruent).

Studies 3 and 4: Student and Faculty Perceptions of Representations, Models, and Modeling in Chemistry

Current studies on tertiary students' representational competency in Organic Chemistry, particularly as it relates to the skills necessary to translate between 2D diagrams, have largely focused on the cognitive gains achieved through students' interaction with 3D concrete and virtual models in the learning environment (Barnea,

2000; Savec, Vrtacnik, & Gilbert, 2005; Stull et al., 2012; Wu et al., 2001; Wu & Shah, 2004). However, additional research suggests that it is equally plausible that student and faculty perceptions of representations and other types of models may also have a dramatic impact on the learning process and the type(s) of instruction taking place in the classroom (Dalgety & Coll, 2005; Ferk, Vrtacnik, Blejec, & Gril, 2003; Grosslight et al., 1991; Treagust et al., 2002). The studies described below intend to explore this latter claim.

Participant sampling procedure. Participants were selected, at random, from all current Organic Chemistry I students and faculty at Andrews University. With their consent, 27 students took part in the pilot phase of the survey protocol. 187 student participants took part in the formal survey phase of the study, with 48 of these same students participating in follow-up interviews. Three faculty consented to take part in the classroom observation and interview phases of the study. Participants were not selected on the basis of any qualifying factors, such as level of experience using concrete models, academic major at the university, or tenure status. Student participants received course credit or \$20 for their participation in the study, as approved by the university's IRB. Faculty received no compensation for their participation.

My Views of Models (MVM) survey. Student participants completed the MVM, which was adapted from the *Student Understanding of Models (SUM)* survey described by Treagust, Chittleborough, and Mamiala (2002). The *SUMS* instrument was chosen as the basis for the development of the MVM survey because it was initially constructed

based on data from studies exploring students' understanding of the role of models in science and, more pertinently, the use of chemical models in teaching Organic Chemistry (Treagust et al., 2002; pp. 358-359). The eight dimensions explored in the MVM survey are presented in Table 1.

Table 1.

Dimensions of the My Views of Models (MVM) survey

Dimension	Description
MR	Models as multiple representations
ER	Models as exact replicas
UM*	The types and general uses of chemical models
CNM	The changing nature of models
MTV**	Models as tools for visualization
EUM**	Experts use of models and representations
MUC**	Model use in the classroom
DUM**	Differences in use of models and representations across scientific disciplines

* The UM dimension collapses items found on Treagust and colleagues (2002) ET and USM scales

** Indicates a new dimension found in the MVM.

Items in the survey were presented on a 5-point Likert scale, and participants were asked to provide a ranking ranging from strongly disagree ("1") to strongly agree ("5") for each item. The purpose of the survey was to provide initial insights into students' perceptions of chemical visualizations, namely 2D diagrams and 3D models, that would also serve, in

part, to guide the development of questions for the semi-structured interview phase of the study.

The survey was administered in two rounds. An initial pilot was conducted with a small cohort of students and faculty to assess the validity of the MVM. This was accomplished in two ways. First, questions on the survey were examined and approved using a “panel of experts” technique (Davis, 1992). With their consent, 27 student participants were then asked to complete the survey and to provide feedback regarding the structure and wording of items on the survey, as well as the reason for their score selection on each item. This latter process was designed to ensure that the responses participants’ indicated on the survey were of the same level of sophistication as the rationales they provided for selecting those responses. This process resulted in the elimination of two items on the survey, which were found to be redundant and/or non-germane to the scope of the survey, as well as better articulation of the survey instructions.

This process also demonstrated that the majority of students (>95%) were using scale/physical models as a referent for defining what constituted a model in the field as they were completing the survey (this was later found to also be the case in the formal round of survey administration), though no definition for the term “model” was explicitly provided in the survey instructions, as many students prefaced their responses with such statements as: “the ball-and-stick model does...” or “models, such as the ball-and-stick model, show...”. After revision, a finalized version of the survey was administered to 187 participants. It is important to note that this survey was administered prior to conducting interviews, in part, to eliminate the bias group think (in the case of focus

group interviews) could have had on how students came to conceptualize what constituted a “model” in Organic Chemistry.

Semi-structured interviews. Forty-eight student participants completing the MVM survey were randomly selected to take part in the interview phase of the study. These participants were either interviewed individually or as part of a focus group consisting of no more than five students. I conducted all interviews alone. The merits and drawbacks of each of these interview protocols are complementary, and focus groups preceded the individual interviews such that the individual interviews helped provide additional depth and detail to supplement the focus group findings (Morgan, 1997). It is important to note, however, that the themes emergent from both the individual and focus group interviews were found to be largely isomorphic, highlighting consistency across these interview approaches. A semi-structured interviewing technique was used to accommodate for nuances and issues raised during the course of the interview (Drever, 1995), and therefore the interviews ranged from 30 – 45 minutes in length. Interview items expanded upon questions found in the MVM survey, specifically topics pertaining to students’ experiences using different forms of visualizations in Organic Chemistry, their definition of what constitutes a representation or model in Organic Chemistry, their perceptions of the role of models in chemistry teaching and learning, and their views on how models and representations are used by experts in the field.

All faculty, with their consent, also took part in an individual, semi-structured interview. The intent of these interviews was identical to that described above. However, faculty were also asked to respond to questions regarding their pedagogical

preparation as chemistry teachers, perceived obstacles to using models in classroom instruction, and differences in how they approach visuospatial tasks in the discipline versus how they teach students how to approach these same tasks. This second set of questions was designed primarily to account for variation in pedagogical training and teaching expertise (based solely on years of teaching in the field), particularly as it related to and influenced classroom instruction. Sample faculty interview questions can be found in Appendix F.

Classroom observations. Faculty lectures were videorecorded during sessions in which 2D diagrams (Dash-Wedge, Newman, and Fischer) were introduced and stereochemical relationships between these representations were discussed. All class sessions were 50 minutes in length, and these topics spanned, at most, two class meetings. These observations were conducted with the intent of documenting the type(s) of instruction occurring, including the use of models as instructional aids, and the faculty-student interactions taking place in the classroom (Ing, 2009).

Summary of quantitative analyses. Student responses to the MVM survey were entered directly into SPSS (IBM®) and analyzed using exploratory factor analysis with varimax rotation. Bartlett's Test of Sphericity was significant ($p < 0.001$), and a Kaiser-Meyer-Olkin (KMO) value of 0.781 was obtained, confirming that factor analysis was an appropriate statistical method to use in this case. This process resulted in the loading of correlated survey items onto their respective scales or constructs, which are identified in Table 2. The reliability of emergent scales was determined based on Cronbach's alpha

values, with values greater than or equal to 0.6 indicative of acceptable levels of reliability (Treagust et al., 2002). Item-to-total correlations were further calculated to ensure that students' responses to each scale were consistent. Descriptive statistics (e.g., percentage of students who agreed, were not sure, or disagreed) for each item were also tabulated.

Summary of qualitative analyses. Classroom observation data were analyzed and interpreted by myself and one other member of the research team on a continuous basis. Videorecordings were transcribed using InqScribe (Inquirium, LLC) and a descriptive interpretive approach applied to identify thematic patterns in the data (Smith et al., 1995). Given the nature of the study, particular emphasis was placed on themes related to use of models in classroom instruction, instances of illustrating 2D-3D relationships of molecules (either with or without the use of supporting models), and the introduction and practical use of representations and models in teaching about various forms of these visualizations.

Interview data obtained from both students and faculty were transcribed by myself and one other researcher using InqScribe (Inquirium, LLC) software. Member checking was employed to ensure accuracy of transcripts (Creswell, 2008). Data was coded in two phases. The first phase was an initial coding procedure, the sole purpose of which was to generate codes and label related data without concern about the numerosity of codes. Focused coding was subsequently used to eliminate and collapse initial codes, as well as discern relevant thematic patterns in the data (Berkowitz, 1997; Smith et al., 1995). In most instances throughout the results and discussion section of this study,

qualitative interview data is presented *in tandem* with quantitative data to highlight the interconnectedness between data obtained from each of these approaches.

Connections Across Studies

Strengths and complementarity of data collection methods. The intent of this research is to establish referential connections between students' use of concrete models, their perceptions of models and modeling in Organic Chemistry, and faculty perceptions and uses of models in chemistry instruction to create a representative account of how these factors influence student success at translating between common 2D representations (Dash-Wedge, Newman, and Fischer diagrams) in the field. The individual studies described in this section employed a mixed methods approach to address this goal. The primary purpose for adopting a mixed methods design for this series of studies was complementarity, with secondary purposes pertaining to triangulation and expansion (Creswell, 2008).

Specifically, the combination of proposed quantitative and qualitative methods aimed to provide a vivid and rich description of students' representational competency in Organic Chemistry that exceeded that which was achievable by use of either methodology alone. In addition, use of these methods was intended to increase the interpretability and external validity of the research and to reduce potential bias (a particular concern of qualitative research) that might be introduced. This was accomplished in two key ways.

First, both the quasi-experimental quantitative studies on students' use of concrete models and the initial MVM questionnaire were designed to collect data from a much

larger sample than could be achieved by use of either the individual or focus group interviews alone. This served to increase the generalizability of the research findings and provide an in-depth, informative account of the role these factors have in shaping students' representational competence. However, the types of tasks and items presented in the data collection instruments used in these studies were close-ended; thus, the observation and interview techniques allowed for expansion of initial findings and exploration of the perceptions and experiences of both students and faculty as it related to models and modeling in Organic Chemistry. This latter, open-ended component was particularly crucial, as research on student and faculty perceptions of modeling in the field is limited.

Secondly, while the qualitative and quantitative studies were designed to ensure complementarity *in tandem*, the quantitative and qualitative methods themselves were designed to be complementary by specifically functioning to increase internal validity through triangulation. Hawkins (1974) asserts that the classroom is a space influenced by student-faculty-content interactions, and that each of these facets must be taken into consideration when properly describing educational contexts and the ways of knowing and learning taking place in these contexts. Accordingly, the quantitative methods I chose to utilize sought to capture the multitude of student-content-context interactions related to concrete model use by offering a rounded discussion of the influence of modes of model presentation (e.g., pre-built, used alone versus in conjunction with 2D diagrams) on student learning, thereby avoiding an overreliance on or over-attribution of any one characteristic or feature of models on the learning process.

With regard to the perceptual studies, though student-faculty-context interactions could be discerned through use of only a single instrument, the combination of survey, interview, and classroom observation protocols was intended to provide a more complete account of the relationship between perceptions of modeling and student learning in the field. Furthermore, each instrument was designed to corroborate and shed light on findings obtained through use of the other data collection methods. The inclusion of open-ended, qualitative items was particularly critical when considering interpretation of the MVM survey, as the survey itself was not modified once the final version was administered, nor could inconsistencies be clarified simply by analyzing the survey data alone (Bhattacharyya, 2007; Creswell, 2008).

Limitations and considerations. While this research is intended to provide a more declarative account of how novices make use of concrete models when translating between 2D chemical representations and why they either elect or do not elect to do so, there are several limitations that must also be considered. First, the studies described herein focus solely on students and faculty at Andrews University who are either enrolled in or are teaching Organic Chemistry I at the university, respectively. While the findings from these studies are nevertheless generalizable to a certain degree, it should be cautioned that the data do not, therefore, speak directly to students and faculty enrolled in or teaching advanced courses in Organic Chemistry nor, necessarily, to students and faculty at two-year or liberal arts institutions.

Additionally, because all students and faculty currently engaged in Organic Chemistry I courses at Andrews University were eligible to take part in this research, the

findings generated do not speak to all confounding factors that might mediate students' use of concrete models when solving representational translation tasks in the domain. Those studies detailing students' perceptions of models and modeling in the classroom, for instance, are not designed to provide a comparative account of the similarities and differences in non-majors versus majors perceptions nor to show how students engaged in chemistry research might possess differing views of models compared to their non-researcher peers, though these facets would certainly be worth exploring. However, it is highly likely, simply by chance, that the student and faculty population taking part in the research described in this dissertation contained a subset of these individuals.

Lastly, my research is not intended to provide a longitudinal account of student learning as a result of (dis)use of concrete models in Organic Chemistry and the influence of perceptions of modeling on this process. This is a necessary area for future exploration that could, perhaps, best be achieved by conducting a longitudinal classroom intervention study that would complement existing, short-duration studies in the field.

CHAPTER 4: THE IMPACT OF CONCRETE MODELS ON STUDENTS' ABILITY TO TRANSLATE BETWEEN 2D REPRESENTATIONS IN ORGANIC CHEMISTRY

To Build or not to Build: That is the Question

Chemistry is a domain reliant upon representations, from chemical formulas and reaction mechanisms to molecular diagrams and concrete models (Gilbert, 2005). This ubiquity predicates that the successful chemist be able to appropriate, manipulate, and translate between various forms of visualization. While experts can complete this task with relative ease, research suggests that novices often struggle to make meaning of and understand the relationship between various forms of representation in the field (Kozma & Russell, 1997). Specifically, because chemistry is such a spatially-oriented domain, novices often fail to appreciate the deeper structural relationships between 2D and 3D depictions of molecules and other chemical phenomena. To address this concern, a growing body of research has called for the use of concrete manipulatives designed to bring the three-dimensional world to life (Bivall, Ainsworth, & Tibell, 2011; Copolo & Hounshell, 1995; Stull et al., 2012). Doing so, this work argues, will scaffold novices' representational competency in the discipline.

In the field of Organic Chemistry, Stull and colleagues (2012) used a quasi-experimental approach to demonstrate the import models have for improving a novice's capability to translate between different representations. Specifically, these authors showed that when students are provided with access to concrete models and make purposeful *use* of these models, they are significantly more successful at translating between two, 2D diagrams of a given molecule than their peers who either do not have access to models or do not choose to use the models to solve the translation tasks.

Furthermore, Stull and colleagues noted that it is the student's ability to align the model to match the target diagram coupled with their level of spatial ability that drive performance on these tasks. These results highlight a very real need to attend to *how* students are making use of models and how spatial aptitude factors into that equation.

However, the generalizability of Stull and colleagues (2012) findings is constrained by the context of their study. Students are provided with pre-built models that, in some cases, are aligned to match the initial 2D diagram, and, in all but the first study, are encouraged to use these models to solve the representational translation tasks presented to them. While the latter half of this statement may hold true in most traditional Organic Chemistry classrooms (van Driel & Verloop, 2002), there is a wide degree of variation in regard to how students interact with models in settings of this nature—from never being exposed to models to simply viewing a teacher lecture model of a molecule to building models of their own. For this reason, the particular series of studies I describe below seeks to explore how model orientation (i.e., how the model is presented to the student for use) influences how students made use of concrete models and how this, in turn, influences their performance on representational translation tasks similar to those administered to the participants in Stull's study.

Specifically, a mixed methods approach was employed to address the following questions:

- 1. How is student performance on representational translation tasks (RTTs) differentially affected by having access either to no concrete models, pre-built models, or a modeling kit for use during the RTT assessment?**

- 2. Which translation task(s) is/are the most difficult for students to perform, and what is the most common error they make when completing these tasks?**
- 3. What behaviors do students perform when working with models, why do they elect (or not elect) to use models, and how do these behaviors correlate with success on RTTs?**
- 4. To what degree is spatial ability and modeling behaviors predictive of success on RTTs?**

Similar to those findings reported by Stull and colleagues (2012), I hypothesized that both those students with high spatial ability and those who make frequent use of models on the RTT (regardless of level of spatial aptitude or modeling treatment condition) would exhibit the greatest performance on the assessment. In other words, I suspected that spatial ability and model use would be predictive of success on the RTT. It is important also to note that by model use, I am referring specifically to a student's ability to align the model to match the desired target diagram indicated in the translation task, rather than simply any random act of model use.

In specific regard to my second research question, I anticipated that students would have the greatest difficulty completing problems that required translation to or from a Fischer projection. In these cases, I thought it likely that students would draw a larger number of enantiomers than exact conformers of the molecule illustrated in the task as a result of failing to remember that the Fischer must be in an eclipsed conformation according to diagrammatic conventions. This hypothesis is supported by

anecdotal evidence as well as previous empirical findings illustrating that students have increased difficulty performing these types of tasks (Kumi & Dixon, in preparation; Padalkar & Hegarty, 2012; Stull et al., 2012).

Results and Discussion

The mean spatial ability score obtained on the *Visualization of Views* test by participants in the No Model ($M = 13.79$, $SE = 1.19$), Pre-Built Model ($M = 14.23$, $SE = 1.21$), and Model Building ($M = 13.88$, $SE = 1.16$) cohorts did not differ significantly ($F(2, 107) = 0.038$, $p = 0.962$). Kappa statistic values for RTT item coding and videocoding were 0.93 (95% CI [0.88, 0.98]) and 0.88 (95% CI [0.82, 0.94]), respectively, indicating high levels of agreement between raters on both measures.

Overview. In this section, I detail four major findings in relation to the original research questions. Specifically, I demonstrate that students' accuracy on representational translation tasks is mediated both by their use of concrete manipulatives on these items and by their level of spatial ability. I show, importantly, that while both low- and high-spatial students make relatively equal use of manipulatives, those individuals who align the models to match the target diagrams requested of them perform significantly better on the RTT assessment than those individuals who either use models infrequently or not at all. Additionally, I provide evidence of rationales for why students either elected or did not elect to use manipulatives on the assessment.

Greater accuracy on RTTs is found only for participants who use models.

An initial one-way analysis of variance (ANOVA) test was performed to ascertain whether mean performance differences on the RTT existed between participants in the No Model ($M = 9.06, SE = 0.92$), Pre-Built Model ($M = 10.72, SE = 0.86$), and Model Building ($M = 10.06, SE = 0.88$) treatment conditions. This test revealed no significant differences between groups ($F(2, 107) = 0.900, p = 0.410$), suggesting that the manner in which models were presented to students for use did not have a significant effect on performance outcomes on the RTT assessment.

While this was the case, previous work by Stull and colleagues (2012) indicates that simply having access to concrete models is not sufficient to promote learning; rather, it is the *use* of these models that is correlated with greater success on translation tasks. For this reason, participants in both the Pre-Built Model and Model Building conditions were aggregated into a single modeling group and then stratified into “users” (i.e., those who made use of models on 50% or more of tasks) and “non-users” (model use on <50% of tasks), the intent being to identify whether mean performance differences on the RTT existed between these groups (see Table 2 for mean scores stratified by group).

Table 2.

Mean Performance Scores on the RTT Stratified by User Status

Group	<i>N</i>	Drawing Accuracy; <i>M (SE)</i>
Access to Models	72	10.20 (0.62)
Users	14	11.88 (1.03)
Non-Users	58	9.60 (0.74)

An independent t-test was performed to compare the user and non-user groups, revealing a marginal, statistically significant difference in performance between cohorts ($t(70) = -1.811, p = 0.074, d = 0.54$). These results suggest one of two things. First, because students in the study cohort were already correctly answering 50% or more of the problems on the RTT, even in the No Model condition, having access to models may not have provided any additional benefits. Alternatively, and perhaps more important to understanding the role of models in enhancing a novice's representational competency, the overall *limited* use of models by participants in the Pre-Built Model and Model Building groups may underrepresent the potential models have in promoting student's understanding of the relationship between the three-dimensional nature of molecules and their 2D depiction. I explore this second conjecture in greater detail in the subsequent section.

Exploring how participants use models. Descriptive analyses indicate that models were used, in any fashion, on 23% ($M = 4.17, SE = 0.72$) of tasks by 49% of the modeling population ($n = 72$). Twenty-two (22) of the participants in the Pre-Built condition used models. 55% of these individuals used models frequently (i.e., on 50% or more of the translation tasks), while the remaining 45% used them infrequently. Contrastingly, thirteen (13) of the participants in the Model-Building group made use of models. Only two of these individuals (15%) constructed and used models frequently on the RTT assessment. The remaining 85% used them infrequently. There are two likely reasons for why these patterns of model adoption emerged.

First, despite the fact that students were encouraged to make use of the models, they still may have felt unsure about how a given model could be utilized to solve a particular translation task. Informal conversation with participants following the RTT suggested this might be the case. Take, for example, the following exchange with one student in the Pre-Built condition:

Researcher: Tell me a little bit, then, about why you chose not to use models in this assessment.

Brandon²: Well, I felt the models *could* be helpful, but I knew once I moved them, I couldn't get them back to how you had them in the first place.

Researcher: So... you... tell me if this is correct... you were afraid that if you moved the model out of place that you wouldn't be able to rotate the model to get it back to the start position?

Brandon: Yeah, like, I trust that you have it oriented the right way now, but I don't trust myself to get it back to that position if I start messing around with it.

In a theoretical sense, though Brandon went on to be relatively successful at completing the RTT, this exchange suggests either that students may lack the representational skills necessary to establish the relationship between parts of the model and parts of the diagram, and/or that they lack confidence in their ability to manipulate concrete models

² A pseudonym. Pseudonyms will be used consistently throughout this dissertation when referring to individuals or locations.

(i.e., they have low self-efficacy in this regard or feel that a model must exist in a certain orientation). Evidence that students hold these beliefs are reported elsewhere in the literature (Stull et al., 2012).

Secondly, for those students in the model-building cohort in particular, the low frequency of model use likely reflects a cost-benefit tradeoff. In other words, because constructing models is a time-consuming task, students might have been more likely simply to apply heuristic approaches to solving the RTTs than to build models *ab initio* if they felt certain the heuristic approach would guarantee them the correct answer to the problem. The following student interview corroborates this claim:

Researcher: Can you tell me why you chose not to construct and use models to solve these tasks?

Kyle: I didn't need to. I thought the problems were pretty straightforward, and it would have taken me too long to build the models.

Researcher: So you feel pretty confident that you completed them [the tasks] accurately using your own strategies? ...and what strategies?

Kyle: Yeah, I mean, I think I did just fine.

Kyle: I just did them step-by-step like I've done with other problems like this.

Researcher: OK. So, like, following a set of rules.

Kyle: Mmhm.

Importantly, responses of this nature were provided by more than 15% of participants who did not elect to engage in modeling during the course of the RTT, suggesting that preference for algorithmic versus models-based approaches is not anomalous among novices in the study population.

Though not an examination of students' model-building practices, one study by Stieff and colleagues (unpublished), in which novices received instruction on how to use models to solve RTTs, yielded similar qualitative interview data from multiple participants suggesting that the top two deterrents of model use for students are lack of or no time to work with models in practical settings (such as on exams) and limited instruction on how to build models for use to complete visuospatial tasks. Taken together, these are both very real concerns that must be addressed if we wish to promote models as effective problem-solving tools in the domain.

In the present study, it is interesting to note, however, that when non-builders such as Kyle were asked to construct a model of the Newman diagram illustrated in problem 17 of the RTT, all but one of them ($n = 23$) were capable of doing so. Despite this, only about half of these individuals were successful at performing the translation task using the model when asked to do so. This observation favors the notion that students likely do *not* lack the requisite skills necessary to construct models based on 2D representations, but rather that they do not know how to *use* them effectively as problem-solving tools or find them too onerous to build, possibly because no one has ever indicated to them how to accomplish these tasks effectively and efficiently. For this reason, a closer examination of students' modeling behaviors was conducted.

For the purpose of the study described here, participants’ modeling practices were dissected into four discrete actions: a) no manipulation or construction of the model; b) Match-Align behavior, in which the constructed or pre-built model was oriented such that it aligned to the backbone of the 2D target diagram; c) Misalign behavior, in which the constructed or pre-built model was oriented such that it was not aligned to match the backbone of the 2D target diagram; and d) gesturing, which the literature reports can be an effective way for students to map the spatial placement of substituents between the 2D diagram and the 3D physical model (Scopelitis, 2012). Note that because gesturing occurred on only a small percentage of tasks (see Table 2) across all individuals in the study population, deictic and iconic gestures were collapsed into one measure. The mean proportion of tasks on which each behavior was observed is reported in Table 3 below for the No Model, Pre-Built Model, and Model-Building cohorts:

Table 3.

Comparing Participant Modeling Behaviors for No Model, Pre-Built Model, and Model-Building Cohorts

Treatment Condition	<i>N</i>	No Manipulation; <i>M (SE)</i>	Match-Align; <i>M (SE)</i>	Misalign; <i>M (SE)</i>	Gesturing; <i>M (SE)</i>
No Model	36	.92 (.03)	-	-	.08 (.03)
Pre-Built Model	36	.54 (.07)	.28 (.04)	.09 (.06)	.10 (.06)
Model-Build	36	.78 (.08)	.13 (.08)	.09 (.04)	.05 (.03)

These data re-portray what was initially seen in the descriptive analyses above—namely, that the majority of students do *not* make use of concrete models to solve representational translation tasks on the RTT assessment, and thus resemble the No Model cohort, who did not have access to models in the first place. It is therefore not surprising, in this case, that student performance on the RTT across all treatment conditions was found to be roughly equivalent. However, these analyses alone do not explain why students did not manipulate models on the majority of tasks. The perceptual studies described in Chapters 5 and 6 begin to address this concern, and so we will return to this topic at a later point in time.

The second most frequent behavior observed for both the Pre-Built Model and Model-Building groups was to align the model to match the target diagram. Post-hoc correlation and chi-square analyses showed that this behavior was not significantly associated with either a participant's level of spatial ability or with a particular type of translation task (e.g., translating from a Dash-Wedge to a Newman diagram). In the majority of cases (85%) where a Match-Align behavior was observed, it was performed at the start of the task or during the task rather than to check one's work after drawing the target diagram. This demonstrates that students who do elect to use models on the RTT are likely incorporating them into their problem-solving repertoire to support spatial and relational reasoning and current representational skills rather than as a post-task fallback mechanism. These students, including participants in both the Pre-Built and Model-Building treatment conditions, frequently reported in post-task interviews that the concrete models had been of particular value “across the board” because they allowed for

the molecules to be “easily visualized in 3D” and were “absolutely essential for being able to complete the task correctly” (Student interviews, Fall 2012).

In comparison, misalign and gesturing behaviors were observed in relatively low frequency for participants in both the Pre-Built Model and Model-Building cohorts. Because it was unclear from these data whether or not those behaviors had a significant effect on students’ performance on the RTT, Pearson-moment correlation analyses were performed. Results indicated no significant relationship between these behaviors and raw performance on the representational translation task assessment ($p > 0.430$ for all analyses). In this context, there are both positive and negative implications associated with these findings. On the one hand, a low incidence of misaligning the model in relation to the target representation indicates that participants who *do* choose to use concrete manipulatives are largely doing so in ways that are effective for solving the translation tasks presented to them.

Infrequent use of gesturing behaviors, on the other hand, can potentially restrict students’ chances of accurately completing items. Deictic gestures directed toward the concrete models used in the RTT have been previously shown, for example, to aid students in coordinating the placement of substituents on the model with the arrangement of substituents they are attempting to draw on the skeletal structure of the target diagram (Stull et al., 2012). It is plausible that these same gesturing behaviors could have likewise been effective for students in this population. However, this conjecture is certainly not meant to imply either that gesturing is an useful strategy for all individuals or that, collectively, these same findings regarding student behavior will emerge across all settings.

Participants have the greatest difficulty with Fischer translation tasks. In addition to examining the association between model use and success on the RTT as a whole, I also sought to briefly examine whether differences in student performance existed on specific translation task subsets. Specifically, I wanted to compare student performance on tasks in three categories: a) those tasks involving translation between Dash-Wedge and Newman diagrams; b) those tasks involving translation between Newman and Fischer diagrams; and c) those tasks involving translation between Dash-Wedge and Fischer diagrams. This decision was made based on empirical evidence in the field, which suggests that students often struggle with understanding the conventions of the Fischer projection (Kumi & Dixon, in preparation). Given that there were no overall significant differences in performance found based on model access or mode of presentation, the entire study population ($n = 108$) served as the unit of analysis.

A repeated-measures ANOVA with Lower-Bound correction was performed, revealing that students' scores on items requiring translation between Dash-Wedge and Newman diagrams ($M = 4.55$, $SE = 0.17$), items requiring translation between a Newman diagram and a Fischer projection ($M = 2.81$, $SE = 0.23$), and items requiring translation between a Dash-Wedge diagram and a Fischer projection ($M = 2.58$, $SE = 0.22$) were significantly different ($F(1, 107) = 56.26$, $p < 0.001$, $\eta^2 = 0.345$). Pairwise comparisons with Bonferroni corrections demonstrate that there was a significant difference in performance between Dash-Wedge/Newman tasks and Newman/Fischer tasks ($p < 0.001$) as well as Dash-Wedge/Fischer tasks ($p < 0.001$), but not between Newman/Fischer tasks and Dash-Wedge/Fischer tasks ($p = 0.393$). Post-hoc descriptive analyses identified that, in instances where inaccurate drawings were produced for Fischer tasks, students most

frequently drew a diastereomer (40% of instances) or enantiomer (58% of instances) of the molecule. Very few students performed another type of error—such as drawing the wrong type of representation (e.g., a Newman when the target diagram was to be a Fischer projection) (2% of instances). No correlation between frequency of model use and type of translation task was observed, suggesting that differences in performance on each subset of tasks was indeed reflective of students not understanding the conventions of the Fischer projections themselves.

Collectively, these findings are in agreement with previous reports in the field (e.g., Stull, 2012), which have demonstrated that novices tend to draw stereoisomers on visuospatial tasks of this nature that require translation between two diagrams. It was common for students in my study population to informally report that Fischer projections were more confusing to understand than the Dash-Wedge or Newman diagrams because they “showed the least amount of information about the 3D structure of the molecule” (Student interview, Fall 2011). It is interesting to note that, in fact, the Fischer projection defies certain conventions adopted by the other diagrams. The solid lines in a Fischer projection, for instance, are not always within the plane of the page, although this is what a solid line is used to represent in a Dash-Wedge diagram. Furthermore, students’ academic experiences in Organic Chemistry courses can often exacerbate this situation. Several Organic Chemistry textbooks, for example, discuss Fischer projections several chapters after Dash-Wedge and Newman diagrams are introduced (in a section on carbohydrate chemistry rather than stereochemistry), and practice problems found in these texts often require students to do little more than fill in substituents on partly pre-constructed diagrams of a Fischer projection (Kumi et al., 2013). The use of concrete

manipulatives to facilitate students' understanding of the Fischer projection is certainly worthwhile; however, it is more of a necessity that those global concerns discussed above are addressed first.

Spatial ability and Match-Align behavior are correlated with success on the RTT. Though the Match-Align behavior was exhibited on only a relatively small percentage of problems across all conditions, I felt it important to examine what relationship this action had to student success on the RTT as a whole and on each of the translation type subsections, as previous studies have demonstrated the importance of this behavior to student success on RTT items (Stull et al., 2012). While an analysis of the Pearson coefficient correlation revealed a weak, positive relationship between participants' use of the Match-Align behavior and their success on the RTT ($r = 0.241$, $p = 0.012$), no significant correlations were found between aligning the model to match the target diagram and success on any individual set of translation problems, either for the collective model cohort (both Pre-Built and Model Building) or for the individual groups themselves. This confirms that students' use of the Match-Align strategy was distributed across all problem types.

Importantly, though frequency of model use was not linked to participants' level of spatial ability, previous evidence in the field (Stieff, Scopelitis, et al., in preparation; Stull et al., 2012) suggested that a closer examination of the relationship between spatial ability and performance was warranted, independent of whether participants used models to complete the RTT. Pearson correlation coefficients for this analysis are presented in Table 4.

Table 4.

Pearson correlation coefficients describing the Relationship between Spatial Ability and performance on the RTT and individual translation subtypes

Performance Item	<i>r</i>	<i>p-value</i>
RTT Assessment	0.471	< 0.001*
N-F ¹ Sub-score	0.331	0.049*
F-N Sub-score	0.369	0.029*
DW-F Sub-score	0.436	0.008*
F-DW Sub-score	0.519	0.001*
DW-N Sub-score	0.211	0.218
N-DW Sub-score	0.121	0.483

Notes: ¹indicates translation between a Newman (N) and Fischer (F) diagram. DW = Dash-Wedge diagram.

**p-value* significant at alpha level = 0.05.

As hypothesized, spatial ability was seen to have a moderate, positive relationship with performance on the 18-item RTT assessment. More interestingly, though, possessing higher levels of spatial aptitude appeared to be of most benefit when solving tasks that required translation to or from a Fischer projection. As discussed previously, several studies have shown that students struggle most with these types of tasks (Kumi & Dixon, in preparation; Todd, 1987). Using a pencil-and-paper assessment, Kumi and Dixon (in preparation) tested, for example, the ability of 49 first-semester Organic Chemistry students to translate from a series of staggered and eclipsed Dash-Wedge diagrams to a Fischer projection (or vice versa). The authors found significant differences in student performance that were dependent upon their ability to understand the spatial conventions

of these representations, such as distinguishing diastereomers and enantiomers of a Fischer project from a conformer of the Dash-Wedge representation.

Given that spatial ability levels are highly variable among individuals in the study population and, likely, in many introductory Organic Chemistry classrooms nationwide, it is imperative that efforts be made to ensure the success of both low- and high-spatial individuals in their study of chemistry. Such research, including this work on the role models may have in scaffolding novices' understanding of 2D diagrams in the field, would be ecologically valid not only because translation task items are frequently used in Organic Chemistry courses to assess students' understanding of the three-dimensional nature of molecules (American Chemical Society, 2010), but also because the ability to switch between various forms of representation is necessary for communication in the field. Though these further analyses are outside of the scope of the series of studies included in this dissertation, researchers in the field have already begun to explore the questions warranting such analysis (see, as example, Stieff, Hegarty, & Dixon, in preparation).

Spatial ability and Match-Align behavior are predictive of success on the RTT. Using a simultaneous linear model, participants' overall score on the RTT was regressed on their spatial ability score, as well as the measure of Match-Align modeling behavior, as these variables were found to correlate with success in the previous analysis. Results suggest that, when all variables are taken together, this model explains 30% of variance in participants' scores ($R = 0.550$, $F(2,105) = 17.12$, $p < 0.001$). Spatial ability ($\beta = 0.360$, $p < 0.001$, $sr^2 = 0.220$) and aligning the model to the target representation (β

= 0.210, $p = 0.044$, $sr^2 = 0.030$) were also each found to uniquely predict success after controlling for the other variable. The beta-coefficients for each of these variables suggest that modest gains in student performance can be achieved for each one-point increase or occurrence in spatial ability or Match-Align behavior, respectively. These findings are in agreement with previous research in the field (Stull et al., 2012), which have identified a significant and important link between these two measures and student outcomes on a similar series of translation tasks in Organic Chemistry.

Summary of Findings, Limitations, and Future Directions

This study intended primarily to examine how students' use of concrete models was impacted by model orientation (i.e., pre-built vs. construction required) and what implications this had for student success on representational translation tasks in Organic Chemistry. Though I hypothesized that students in the modeling treatment conditions would, collectively, perform better than the control group receiving no access to models, results from a one-way ANOVA analysis confirmed that this was not the case. There are three reasons why this could have occurred. First, it could have been the case that the models were superfluous. In other words, students' could have possessed sufficient representational competency to complete the translation tasks without the need for models to be present. Indeed, even those students in the No Model condition accurately completed 50% of tasks—more than reported in duplicate studies conducted by my colleagues (Stull, 2012). However, if this were true, one would have expected to observe greater levels of performance across all groups regardless of access to or degree of model

use exhibited by participants in those groups. This was not found to be the case, particularly for tasks requiring translation to or from a Fischer projection.

Second, although students in the modeling treatment conditions were encouraged to use the concrete models to solve the translation tasks, they were not required to do so. Given that students are most familiar with two-dimensional diagrams as a result of their use in lecture and laboratory contexts as well as their prevalence in visual and aural media in the field (e.g., textbooks) (Gilbert, 2005), it would not have been surprising to find, therefore, students taking the idea of model use for granted in favor of applying more 2D-associated heuristic approaches to solving the items on the RTT. In one study examining novices use of alternative strategies for solving stereochemical tasks in Organic Chemistry, Stieff, Hegarty, and Dixon (2010) show, for instance, that students often assign stereochemistry to molecules using analytic rules, such as determination of R/S configuration for Fischer projections.

Though not an *a priori* focus of the present study, informal, post-assessment discussions with students in my study population demonstrated, similarly, that students would often resort to these strategies because “they were the ones my professor taught me” or “I [the student] wanted to use models but was more certain the [heuristic] would provide me with the correct answer” (Student interviews, Fall 2011). Such conversations show that while model use may serve to enhance students’ representational competency and while students may perceive models to be relevant to performing representational translation tasks in the field, it is unwise to assume that they know how to work with these tools to solve such tasks (i.e., that they find them sufficient problem-solving tools). In this case, specific attention needs to be placed on ensuring that students truly

understand how models, being inherently 3D in nature, allow one to more readily comprehend the deeper structural relationships between two-dimensional and three-dimensional representations of a molecule (Bucat & Mocerino, 2009).

Lastly, it was plausible that student performance was not correlated with the type of model presented to them or the potential that models were unnecessary in this context but rather student's *ability* to use these models in purposeful and meaningful ways to complete the representational translation tasks. In other words, it was possible that students found the concrete models to be both necessary and sufficient for solving tasks on the RTT, but only those students who possessed the requisite skills to effectively make use of models to complete these tasks were successful at doing so. Given that Stull and colleagues (2012) noted the significance of this relationship in their own data, I pursued this possibility further. After stratifying participants in the modeling treatment conditions into users (i.e., those who used models on 50% or more of translation tasks) and non-users, it became highly evident that this was, in fact, the case. Specifically, regression analyses indicated that aligning the models to match the target diagrams on RTT items was associated with greater accuracy in completing these items. It is important to note, though, that while this strategy was effective for the participants in this context, it does not preclude that other strategies cannot be equally as effective and perhaps even more useful for other individuals depending upon the situation in which students are being asked to use concrete models.

In addition to exploring the impact of model presentation and use on student performance, this study also examined the importance of spatial ability in predicting student success on the RTT. In accordance with my initial hypothesis, correlation

analyses revealed a moderate, positive relationship between spatial ability and student performance on both the RTT as a whole, as well as on specific tasks requiring translation to or from a Fischer projection. Given that Organic Chemistry is a spatially-demanding discipline (Harle & Towns, 2011), this observation was not surprising, though the link between spatial ability and performance on Fischer problems is notable given increasing empirical evidence identifying student difficulties when completing tasks of this nature (Kumi & Dixon, in preparation).

Furthermore, when considering how spatial aptitude influences students' modeling behaviors, there is always great fear that students with high spatial ability are the only ones benefiting from having access to models because they appear to (or do) intuitively understand how to use these tools. Data from this study suggest that this is not always the case, as no significant correlations between participants' levels of spatial ability and frequency of model use were observed. These results support the conclusion that models-based curricula and instructional tutorials for students on how to use concrete models may be effective not only in allowing low-spatial students to overcome the challenges of mentally imagining and manipulating organic molecules, but also enhancing and reinforcing high-spatial students' performance in the domain.

However, despite the apparent benefits models may have for both low- and high-spatial individuals, it is important to keep in mind that the above study leaves several additional questions unanswered. Principally, this study does not explore, in great detail, *why* students elected either not to use models or to use models in the way(s) that they did. For example, why were students more reticent to construct their own models versus using pre-built models, and were these choices influenced by confounding factors, such as

having access to both 2D and 3D representations of the molecules presented in the RTT? What influence did classroom experience have on students' modeling behaviors? Would performance on the RTT look different for more advanced Organic Chemistry students? I explore some of these questions throughout the remainder of this dissertation.

Focusing on the 3D World: A Shift from 2D to 3D

A substantive amount of research has been conducted across a number of domains exploring how novices make use of concrete models while problem-solving in the context of both quasi-experimental and classroom intervention settings. Many of these studies have been reviewed previously in this dissertation (Stull et al., 2012; Wu et al., 2001, as examples). In the field of chemistry, this corpus of research has shown, by and large, that models are effective problem-solving tools a) when students make purposeful use of them; and b) when they (models) are presented in conjunction with the 2D diagrams they represent. However, from a practical stance, little is currently known about how students use 3D models to translate between diagrams when 2D representations are *not* present.

In the current study, I address this concern by adopting a primarily quantitative approach to explore how students translate between the Dash-Wedge diagram, Newman projection, and Fischer projection representations of molecules either without the aid of concrete models (2D-only) or when they only have access to 3D, physical models illustrating these representations, and no 2D diagrams are shown. Specifically, this study addressed the following questions:

- 1. Is student performance on representational translation tasks (RTTs) differentially affected by experiencing 2D-only versus 3D-only conditions during the RTT assessment?**
- 2. What behaviors do students perform when working with models, and how do these behaviors correlate with success on RTTs?**
- 3. To what degree are spatial ability and modeling behaviors predictive of success on RTTs?**

I hypothesized that students would perform better on the RTT when presented with only the 2D diagrams given the frequency with which students encounter these representations in their classroom experiences and textbooks, as well as in online resources (Kumi et al., 2013). Additionally, I anticipated that students in the modeling condition would be more successful on the RTT only if they were cognizant of how to purposefully manipulate the model to translate from the initial representation to the target representation, for instance by aligning the model to match the desired target representation.

Results and Discussion

The mean spatial ability score obtained on the *Visualization of Views* test by participants in the 2D-only ($M = 14.91$, $SE = 1.32$) and 3D-only ($M = 12.32$, $SE = 1.08$) cohorts did not differ significantly ($t(58) = 1.516$, $p = 0.135$). Kappa statistic values for RTT item coding and videocoding were 0.97 (95% CI [0.91, 0.99]) and 0.86 (95% CI [0.79, 0.92]), respectively, indicating high levels of agreement between raters on both measures.

Overview. In this section, I detail three major findings in relation to the original research questions. Specifically, I show that students in the 3D-only treatment group perform significantly better on the RTT than their 2D-only counterparts and discuss reasons why this might be the case. I demonstrate further that students' accuracy on representational translation tasks is mediated both by their use of concrete manipulatives on these items and by their level of spatial ability. Finally, I show, importantly, that while both low- and high-spatial students make relatively equal use of manipulatives, those individuals in the 3D-only condition who align the models to match the target diagrams requested of them are more successful on the RTT assessment than those individuals who either misalign the model to the target representation or do not use the models at all.

Greater accuracy on RTTs is achieved through interaction with 3D, physical models and not simply “seeing” 2D diagrams. An independent *t*-test was performed comparing the mean proportion of correct answers on the representational translation task set for students in the 2D-only condition ($M= 0.49, SE= 0.04$) with that for students in the 3D-only condition ($M= 0.66, SE= 0.05$). This analysis suggests that participants receiving 3D, physical models alone perform significantly better on the RTT than those receiving only 2D representations ($t(58)= -2.435, p = 0.018$). A Cohen's *d* effect size of -0.64 was obtained, indicating that mean scores on the task differ between groups by approximately six-tenths of a standard deviation.

Further analysis of students' responses indicated that drawing accuracy was greatest on problems involving translation between Dash-Wedge and Newman diagrams

(and vice versa; $n_{\text{total}} = 6$ problems), with students in both the 2D-only ($M_{\text{score}} = 5.23$, $SE = 0.27$) and 3D-only ($M_{\text{score}} = 5.00$, $SE = 0.33$) cohorts drawing correct conformers of the target molecule on >80% of these items. For tasks involving translation to or from Fischer projections ($n_{\text{total}} = 12$ problems), an independent t -test revealed that participants in the 3D-only cohort performed significantly better ($M_{\text{score}} = 6.87$, $SE = 0.67$) than their 2D-only counterparts ($M_{\text{score}} = 3.63$, $SE = 0.66$) by almost a full standard deviation ($t(58) = -3.436$, $p = 0.001$, $d = -0.90$). There are likely two reasons for this observation. First, several students (particularly low-spatial students) across the entire study population failed to remember that Fischer projections must be depicted in an eclipsed conformation—a finding that has been seen previously in studies of this nature (Stull et al., 2012).

Second, for those individuals who *did* accurately recall that Fischer projections must be eclipsed, it seems evident that providing these students with access to and the ability to manipulate models improved their success at completing Fischer translation tasks. This is likely because they could physically place the model in an eclipsed position instead of attempting to mentally rotate the molecule in their mind. As one student stated, “I found it hard to picture it [the Fischer projection] in my head, so I relied more on the model to see whether substituents were coming out towards me or away backwards and used the model to rotate the molecule” (Student interview, Fall 2011 semester), a belief shared by approximately 10% of the study cohort. If this latter observation is, in fact, broadly true across other student populations, then affording more opportunities for students to make use of models inside and outside (e.g., for the purposes of completing homework) of the classroom is integral for promoting novices’

understanding of 2D representations and, ultimately, greater success in Organic Chemistry.

Exploring how participants use models. Participant videos were analyzed for the presence of four behaviors, including: a) No Manipulation of the model (or no access to models); b) Match-Align, which entailed aligning the model to the target representation (i.e., aligning the backbone of the model to match the target representation); c) Misalign, which entailed misaligning the model in relation to the target representation (e.g., positioning the model as a Fischer but forgetting to place the model in an eclipsed conformation); and d) gesturing. The mean proportion of problems on which each behavior was observed is presented in Table 5 below for the 2D-only and 3D-only cohorts:

Table 5.

Participant Modeling Behaviors for 2D-only vs. 3D-only Cohort

Treatment Condition	<i>N</i>	No Manipulation; <i>M (SE)</i>	Match-Align; <i>M (SE)</i>	Misalign; <i>M (SE)</i>	Gesturing; <i>M (SE)</i>
2D-only	30	1.00 (.00)	-	-	-
3D-only	30	.24 (.01)	.47 (.008)	.14 (.003)	.15 (.002)

Interestingly, these data demonstrate that participants in the 2D-only condition did not use any gesturing behaviors, such as iconic gestures, when solving RTTs, though these behaviors could potentially allow for greater success on the translation tasks (Stieff,

2011). In a think-aloud study of 12 Organic Chemistry students' use of imagistic reasoning skills to solve stereochemical and reactions-based problems in the field, Stieff (2011) shows, for instance, that novices often couple mental modeling (an imagistic approach) with gestural movements depicting the rotation of the imagined molecule. Though this did not ensure greater accuracy on a given task, Stieff notes that gesturing did have the potential to lead to increased performance on the administered assessment. Previous work by Stull and colleagues (2012), which examined Organic Chemistry students' use of gestures while completing the same set of representational translation tasks discussed here, likewise illustrated that deictic and iconic gestures had the potential to increase students' accuracy at completing items on the RTT battery.

For those participants who are shown only the 3D, physical model, the most common action was for participants to rotate the model to match the target representation (Match-Align). Previous studies have shown that this often leads to greater success on representational translation tasks (Stull et al., 2012), a factor which I will explore further in subsequent analyses. In addition, although not an *a priori* focus of the study, analysis of participant video illustrated that model use was most common either at the start of the task (21% of participants) or during the task (72% of participants) and not after the task had already been completed (7% of participants). This observation is significant for two reasons. First, it suggests, importantly, that participants are using models to achieve a solution to the task, rather than simply using models to check their work. While there is nothing wrong with using models as a check, these data support a role for models as problem-solving tools. In contrast, a second issue that must be accounted for is that for students who *misalign* the model at any point while solving a given task on the RTT, it is

likely that their performance on the assessment will decrease. I explore this possibility below.

Spatial ability and Match-Align behavior are positively correlated with success on RTTs. Given the substantial degree to which students aligned the model with the target representation, I sought to examine whether a correlation existed between the frequency with which students performed this action ($M= 254.8, SD=4.3$) and their overall score on the RTT ($M= 11.83, SD= 1.57$). A test of the Pearson correlation coefficient indicated a significant, moderate-positive relationship between these two variables ($r= 0.460, p = 0.001$). Though not a strong relationship, this finding suggests that students who are able to purposefully manipulate the model to achieve the desired task of translating the initial 2D representation into the target representation exhibit greater success in completing RTTs than those who do not recognize the functional value of models in performing this same task. Interestingly, a weak negative correlation between the frequency with which participants *misalign* the model to the target representation ($M= 75.6, SD= 1.35$) and their overall success on the RTT ($r= -0.340, p < 0.10$) was also observed, further emphasizing that it is not only access to 3D models that improves student success on RTTs but rather the implicit knowledge of how to use models to solve tasks of this nature. No significant correlation between gesturing and performance was found ($p = 0.46$).

In addition to exploring the above modeling behavior, I also performed a Pearson correlation test to address the potential relationship between spatial ability ($M= 13.61, SD= 6.68$) and participants' scores on the RTT ($M= 10.37, SD= 4.86$). This test was

found to be statistically significant ($r= 0.376$, $p= 0.003$), revealing a moderate, positive relationship between the two variables examined. This finding corroborates previous studies of spatial ability in the field (Stull et al., 2012, as example) and identifies an area where models might be integrated more effectively into instruction especially to scaffold low-spatial students understanding of Organic Chemistry.

While this is the case, it is imperative to note that no significant correlation was found between level of spatial aptitude and the frequency with which participants utilized models to solve the tasks presented on the RTT. In fact, an unplanned, t-test comparison of high-spatial ($M = 13.27$, $SE = 1.24$) and low-spatial ($M = 10.40$, $SE = 1.36$) students' mean score on the RTT for those individuals in the 3D-only condition revealed no significant difference in performance between groups ($t = -1.554$, $p = 0.131$). This suggests that the concern is not, necessarily, the fact that low-spatial students are more reticent to use models than their high-spatial peers, but rather that explicit attention needs to be given to illustrating the relationships between two-dimensional molecular diagrams and their three-dimensional equivalents, as this will likely facilitate students' ability to apply representational skills to solving RTT items. Indeed, if effective model use is contingent upon possessing relatively high levels of spatial ability, then simply providing concrete manipulatives to students (low-spatial students, in particular) is meaningless. Regardless, it is encouraging that because both high- *and* low-spatial individuals are making relatively equal use of models when completing this assessment, providing access to concrete models for use on tasks such as the RTT is not only benefiting those individuals (high-spatial students) who likely could have completed the assessment with relatively high accuracy regardless.

Spatial ability, Match-Align, and Match-Misalign behaviors are predictive of success on RTTs. Using a simultaneous linear model, participants' overall score on the RTT was regressed on their spatial ability score, as well as the Match-Align and Match-Misalign modeling behaviors. Results suggest that, when all variables are taken together, this model explains 42% of variance in participants' scores ($R = 0.646$, $F(3,56) = 13.36$, $p < 0.001$). Spatial ability ($\beta = 0.081$, $p = 0.002$, $sr^2 = 0.104$), aligning the model to the target representation ($\beta = 0.646$, $p < 0.001$, $sr^2 = 0.268$), and misalignment of the model to the target representation ($\beta = -1.014$, $p = 0.009$, $sr^2 = 0.076$) were also each found to uniquely predict success after controlling for all other variables. Examination of the beta-coefficients for these variables indicates that for each additional Match-Align or Misalign action, there was an increase or decrease of almost one correct drawing, respectively. This observation reaffirms an important role for models in helping students to conserve the 3D conventions of molecular structures when depicting them in two dimensions.

I acknowledge that these may not be the only variables predictive of success on representational translation tasks, nor argue that, in other contexts, behaviors such as gesturing (which was not found to significantly correlate with success on RTTs here) will not be indicative of success. However, these analyses provide strong support for attending both to students' level of spatial intelligence and their understanding of the role of 3D models, as these factors appear to highly influence students' success on visuospatial tasks in the field, such as the ones presented here.

Summary of Findings, Limitations, and Future Directions

For novices, the ability to understand and manipulate representations and models is an important step toward achieving expertise in the field. While much research (see, as example, Stull et al., 2012) has demonstrated the power of 3D, physical models in promoting students' understanding of 2D diagrams and enhancing their ability to translate between these diagrams, this study demonstrates that students are successful at translating between diagrammatic forms (e.g., Dash-Wedge, Newman, and Fischer) even when 2D representations are initially absent. Though counter to my initial hypothesis, this finding is particularly intriguing given students increased level of exposure to 2D diagrams as compared to models, at least in the broader university context in which this study was carried out. I argue that the difference may be explained by two factors. First, data indicate that the majority of students in the 3D-only condition aligned the model to match the target representation, suggesting a deeper understanding of how the model might be used, functionally, to solve the tasks presented on the RTT and the importance of preserving the spatial relationships between molecular representations when translating between different 2D diagrams. This is similar to the findings presented in the first study above. Accordingly, it is also plausible in this case that greater attention, practically, to models-based instruction in the classroom (including how to construct models, use models to solve specific tasks, etc.) would appear beneficial to student learning.

Secondly, for those students in the 3D-only condition, the model was the focal point of the task. In other words, students could not initially resort to working with the 2D diagram and instead *had* to make greater use of the models, even if only for a brief

time. The idea of enforcing model use may be debatable, though it appears in the context described here to be beneficial to student learning and success at completing representational translation tasks in the discipline. Additionally, it is interesting that the only difference between the design of the 3D-only condition here and the Pre-Built Model condition in Study 1 is the absence of two-dimensional diagrams. Unfortunately, the fact that this second study was carried out using a different course cohort limits the ability to compare groups. However, the data suggest that initially providing students with access only to concrete models may reduce their cognitive load both because the model itself represents the three-dimensional nature of the molecule it is depicting and because there is no selective pressure to attend to both 2D and 3D forms of visualization simultaneously. Therefore, students may be more inclined to make use of the models to solve RTTs.

This hypothesis is supported by the observation that students in the 2D-only condition did not perform any behaviors, such as gesturing, while completing the RTT, though they were not restricted from doing so. Unlike their 3D-only counterparts, it is likely that these students saw the activity simply as an exercise. In other words, participants adopted a heuristic approach to completing the tasks that deemphasized or discredited the need for re-representing molecules in different 2D diagrammatic forms in the first place. This behavior is of particular concern given that participants in the study population are most regularly placed in classroom contexts where models are not accessible and, therefore, they must rely upon alternative strategic approaches (such as algorithmic methods) to successfully complete visuospatial tasks.

From a broader theoretical and practical standpoint, these findings reinforce the notion that students' representational competence encompasses not only their ability to understand and interpret 2D representations, but also their capacity to "make sense" of 3D models. The success with which students can accomplish this task, as illustrated in the work presented here as well as in previous work in the field (Stull et al., 2012), suggests that models might also be more effectively integrated into classroom instruction to promote understanding of multiple chemical phenomena, especially the spatial and symbolic nature of these phenomena. This, however, begs several questions: What type(s) of support must be in place for faculty seeking to use models in the classroom? What specific content in Organic Chemistry lends itself well to being depicted through models? Do the learning gains achieved by working with models last, in a longitudinal sense? These are all fruitful areas for further investigation.

Furthermore, the limitations imposed by this study generate several important questions worth consideration. Kozma and Russell's (1997) work illustrates, for instance, that one's degree of representational competency increases as a function of experience and expertise in the field. It would therefore be interesting to examine how more advanced Organic Chemistry students, such as Organic II or graduate students in Organic Chemistry, might make use of concrete models to solve the representation translation tasks administered in the current study. Likewise, most of the problems on the current version of the RTT include 4- to 6-carbon molecules. How might student performance be impacted by asking them to translate between more complex molecules containing greater than 6 carbons, and what factors (including model use) might predict success on an assessment of this nature? Such analyses would begin to offer greater

insight into the relationship between task complexity and level of experience in Organic Chemistry and level of representational competence in the domain.

CHAPTER 5: STUDENTS' PERCEPTIONS OF MODELS AND MODELING IN ORGANIC CHEMISTRY

Introduction

Diagrams and concrete models have been an integral component of communicating scientific knowledge for more than a century and have revolutionized the way in which we, as individuals, have come to think and reason about science. Watson and Crick's (1953) discovery of the DNA double-helix and Bohr's model of atomic structure (1913) are but two examples of this revolution in action. For experts, these models have traditionally served as the basis for predicting, visualizing, and explaining both the tangible and abstract complexities of scientific phenomena and the scientific world. However, for novices entering a scientific discipline for the first time, it is often unclear what value these models hold as tools for coming to understand that particular area of study.

In educational contexts, research suggests that although models have long been lauded as useful tools for promoting learning and though they are, at times, an essential part of the chemistry classroom, novice students' views of models are commonly consistent with a naïve realist epistemology (Grosslight et al., 1991). In one quantitative study of 288 Australian junior high school students' perceptions of scientific models, Treagust et al. (2002) show, for instance, that 62% of students believed models "should be exact in every way except for size" and 49% agreed that models must be exact enough such that "nobody can disprove [them]" (p. 363). While this was the case, as many as 20% of the students made mention that there is more to scientific models than simply being duplicates of the original entity they intend to represent. This awareness and the

subsequent diversity in student responses noted by the authors throughout the remainder of the study are significant, suggesting that analysis of students' perceptions may be valuable in coming to understand both why novices elect to use models, including representations, in particular ways to appropriate scientific knowledge as well as how these visualizations supplement students' current representational skill set.

Additionally, though not a direct focus of Treagust and colleagues (2002) study, such findings also urge us to consider what is happening in the classroom itself, as this likely mediates the types of perceptions students form about models and other visualizations in these settings. While I will address this concern in greater detail in Chapter 6, it is important to keep in mind that empirical research indicates that faculty largely incorporate models-based curricula into their classrooms in ways consistent with how they themselves were taught (Coll, 2006; Cosgrove & Schaverien, 1997; Justi & Gilbert, 2002b). In the best case scenario, this results in students developing sophisticated views of models and the role of models in generating scientific knowledge. At worst, faculty may use models in superficial ways that hinder student understanding and do little more than present models as factual byproducts of accepted scientific theories (Treagust et al., 2002). While in reality there is not such a clear dichotomy, it is noteworthy that student perceptions of visualizations may be framed differently based on personal experiences in science courses.

In regard to understanding specifically those perceptions and views of models held by undergraduate students in Organic Chemistry, it is interesting that relatively few studies have explored this issue in great detail. For instance, at the conclusion of their study examining students use of concrete models to solve representational translation

tasks, Stull and colleagues (2012) report that many participants elected not to use physical models because they were confused by the conventions of the models, had never worked with them before, or “did not wish to depend on models because such aids would not be provided on their exams” (p. 426). However, this acknowledgment is brief, and there is no indication that subsequent studies will follow up on these findings.

Likewise, based on qualitative interview data from their study of the impact of a models-based instructional tutorial on Organic Chemistry students’ use of concrete models to solve representational translation tasks (RTTs), Stieff and colleagues (in preparation) illustrate that students are reticent to adopt strategies that involve models when they do not believe they need such tools to solve RTTs or when they feel algorithmic approaches to problem-solving, such as those presented to them in class, are more effective. Though these findings are in agreement with those of Stull and colleagues (2012) and suggest an important relationship between classroom practice and students’ perceptions of models, there is some concern as to whether students’ comments reflect their general beliefs about the role of models in chemistry or if these views are biased by students’ involvement in the intervention.

Regardless, aside from these studies, much of the research performed in this area has been conducted in K-12 contexts outside of the United States and has focused broadly on students’ perceptions of models across *all* scientific disciplines (Grosslight et al., 1991; Treagust et al., 2002, 2004). This is not to say that the results of this body of work are without merit. Rather, this observation provides evidence that additional research categorizing tertiary students’ perceptions of representations and models in chemistry is necessary, particularly by documenting how these perceptions might influence the ways

in which students appropriate these forms of visualization and make use of them across various learning environments.

This small-scale, exploratory study begins to speak to this need. Using a mixed methods design combining both survey and interview techniques, I addressed the following specific questions:

- 1. What views do students hold about the nature of models (concrete or otherwise) and modeling in Organic Chemistry and the potential role models have for learning in the discipline?**
- 2. What perceptions do students have regarding how experts in both the field of Organic Chemistry and in other scientific disciplines make use of models?**
- 3. What functional value do students perceive concrete models have for completing representational translation tasks (RTTs) in Organic Chemistry?**

I hypothesized that because participants enrolled in the study were most likely completing Organic Chemistry I coursework in their freshman or sophomore year, they would still hold realist views of models similar to those of the upperclassmen secondary students discussed by Grosslight and colleagues (1991) and Treagust and colleagues (2002). Furthermore, it was likely that these perceptions would be constrained by students' classroom experiences given that these contexts likely represent the only opportunities students have had to engage in discussing and working with scientific models. Among other possibilities, this could have resulted, for instance, in students perceiving models to be of functional value only in classroom settings involving pre-

scripted tasks that encourage model use (such as the RTT), rather than as malleable and predictive tools used by chemists to address fundamental questions and problems throughout the discipline.

Results and Discussion

Participant descriptive data and factor structure analysis

Participants. This study was conducted with 187 first-semester, Organic Chemistry students at Andrews University, a large Research I institute in the Eastern United States. This course typically enrolls 250-300 students per section per semester. Although some faculty teaching this course use models during lecture, participants in this study received no formal instruction on the use of models in Organic Chemistry, including the use of models to complete representational translation tasks. Therefore, the perceptions of models and modeling discussed below reflect participants' own personal experiences as students taking part in the first-semester Organic Chemistry curriculum at this university.

All 187 students took part in the initial survey round of data collection, which was designed to provide a basal account of students' views regarding models and modeling in Organic Chemistry. Forty-eight students subsequently took part in either a follow-up focus group or individual semi-structured interview designed to elaborate upon findings discerned from analysis of the survey data. Descriptive statistics for these cohorts are presented in Table 6.

Table 6.

Demographic Characteristics of Survey and Interview Participants

Characteristic (Survey Participants)	<i>N</i>	Percent of Population (%)
Gender	187	100.0
Male	73	39.0
Female	114	61.0
Class Standing	187	100.0
Freshman	97	51.9
Sophomore	35	18.8
Junior	18	9.6
Senior	21	11.2
Other (e.g. Post-Baccalaureate)	16	8.5
Characteristic (Interview Participants)	<i>N</i>	Percent of Population (%)
Gender	48	100.0
Male	20	41.7
Female	28	58.3
Class Standing	48	100.0
Freshman	30	62.5
Sophomore	12	25.0
Junior	4	8.3
Senior	1	2.1
Other (e.g., Post-Baccalaureate)	1	2.1

Structural dimensions of the My Views of Models (MVM) survey. Factor analysis using varimax rotation identified eight dimensions in the response items of the MVM survey, which represent eight unique scales in the instrument. These scales are as follows: (1) Models as Multiple Representations (MR); (2) Models as Exact Replicas (ER); (3) The Types and Uses of Chemical Models (UM); (4) Changing Nature of Models (CNM)³; (5) Models as Tools for Visualization (MTV); (6) Experts Use of Models (EUM); (7) Model Use in the Classroom (MUC); and (8) Differences in Use of Models across Scientific Disciplines (DUM) (see Table 7).

The first four scales are described in detail by Treagust, Chittleborough, and Mamiala (2002) and are intended to capture the “breadth of students’ understanding of particular aspects of models” (p. 359) (note: scales three and four in the authors’ work have been, in part, collapsed into scale three in this dissertation based on the findings of my research). Scales six through eight were designed to explore students’ perceptions of how models were used both in the classroom and in the field at large, as well as how the use of visualizations in Organic Chemistry compared to the use of visualizations across other scientific disciplines, such as biology and physics. The EUM scale focuses specifically on the use of models by chemistry experts and includes such items as “Experts do not need to use models, such as ball-and-stick models, because these models are too simple to explain the phenomena experts are interested in studying” (item 29).

The MUC scale was developed based on findings from Stull and colleagues (2012) and Stieff and colleagues (in preparation) that suggested that student views of the efficacy of models were shaped, at least in part, by their classroom experiences.

³ Note that these first four scales represent or are adaptations of those found in the SUMS instrument described by Treagust, Chittleborough, and Mamiala (2002).

Examples of items in this scale include: “Instruction on model use should be provided to students so that they understand how to construct and use models to solve problems in Organic Chemistry” (item 31) and “Students should be permitted to use models on exams and other classroom assessments” (item 32).

Lastly, the DUM scale focuses on how the use(s) of models by individuals in other scientific disciplines is similar or dissimilar to how models are used by chemists. One example of an item in this scale is “Biologists use fewer models than scientists in other disciplines because the processes studied by biologists exist at a macroscopic level and are already easy to visualize” (item 35).

Table 7.

*Factor Analysis of the 35-Item My Views of Models (MVM) Survey**

Item Number	Factor Loadings							
	1: <i>MR</i>	2: <i>ER</i>	3: <i>UM</i>	4: <i>CNM</i>	5: <i>MTV</i>	6: <i>EUM</i>	7: <i>MUC</i>	8: <i>DUM</i>
1	0.60							
2	0.67							
3	0.60							
4	0.58							
5	0.47							
6	0.57							
7	0.68							
8	0.44							
9		0.85						
10		0.72						
11		0.86						
12		0.72						
13		0.80						
14		0.54						
15		0.75						
16		0.49						
17			0.54					
18			0.56					
19			0.60					
20			0.79					
21			0.68					
22			0.72					
23			0.57					
24				0.67				
25				0.88				
26				0.79				
27					0.74			
28					0.70			
29						0.70		0.54
30						0.74		0.62
31							0.68	
32							0.82	
33							0.79	
34								0.62
35								0.72
% Variance	18.3	13.5	6.5	5.1	5.0	4.5	4.1	3.6
Eigenvalues	6.4	4.7	2.3	1.8	1.82	1.6	1.5	1.3

* Items with factor loadings less than 0.40 were omitted (Grosslight et al., 1991; Treagust et al., 2002).

As evidenced in the above data, two items loaded onto two scales. These items were “Experts do not need to use models, such as ball-and-stick models, because these models are too simple to explain the phenomena experts are interested in studying” (item 29), which loaded onto the EUM and DUM scales, and “Experts do not need to use models because they have enough knowledge in the field to solve questions without models being necessary” (item 30), which loaded onto the EUM and DUM scales. These findings were not surprising because there is significant overlap, conceptually, between items 29 and 30, which belong to the EUM scale, and items 34 and 35, which are found uniquely in the DUM scale.

Cronbach’s alpha values were tabulated to assess the reliability of each scale. These values ranged from 0.61 to 0.84, indicating acceptable to high levels of internal consistency for each scale (see Table 8). All item-to-total correlations were 0.431 or higher; thus all items were retained in the survey for purposes of analysis.

Table 8.

Descriptive Statistics and Cronbach's Alpha Measurements for the Eight MVM Scales

<i>Scale</i>	<i>Number of Items</i>	<i>Mean</i>	<i>Standard Deviation</i>	<i>Cronbach's Alpha</i>
Models as multiple representations (MR)	8	3.97	0.51	0.78
Models as exact replicas (ER)	8	3.27	0.74	0.84
Types and uses of models (UM)	7	3.85	0.64	0.82
The changing nature of models (CNM)	3	4.32	0.62	0.83
Models as tools for visualization (MTV)	2	4.40	0.61	0.64
Experts use of models (EUM)	2	3.48	0.83	0.61
Model use in the classroom (MUC)	3	3.66	0.75	0.75
Differences in model use across disciplines (DUM)	2	2.85	1.01	0.79

Mann-Whitney U-tests revealed no significant differences in response between students of different class standing or gender on any of the scales.

Students' perceptions of the nature of models and modeling in Organic

Chemistry. Despite a growing body of research that highlights the potential benefits afforded by models (e.g., Stull et al., 2012), a fundamental concern remains as to how novices perceive models and modeling in the context of their study of Organic Chemistry. It is unsafe to assume, for instance, that because select students find value in using concrete models to solve representational translation tasks in the domain, this

precludes that they (and others) necessarily possess the representational skills required to understand the relationship between these models and other visualizations in the field. It also does not guarantee that they comprehend the broader implications modeling may have for learning and success in Organic Chemistry. In fact, as I reported in Chapter 4, many students elect *not* to make use of models (here, concrete manipulatives) even when they are provided with access to them.

One rationale for this observation is that students retain naïve realist epistemologies of models—ones in which models are viewed as static, factual entities of the phenomenon they represent (Grosslight et al., 1991)—that prevent them from seeing these manipulatives as effective tools for problem-solving and reasoning in the domain. Analysis of data from the MVM survey (Table 9) showed, for instance, that 56.3% of students either were undecided about or agreed that a model should be an exact replica (item ER/9). More than 66% of participants reported that a model needed to at least be close to the real thing, with 80.8% agreeing that a model needs to be close to the real thing by giving correct information and showing what the object/phenomenon looks like (item ER/14), 45.1% agreeing that a model should be very exact in every way except for size (item ER/13), and 30.3% agreeing that a model needs to be close to the real thing by being very exact, so nobody can disprove it (item ER/11).

When asked to discuss and describe examples of chemical models or visualizations that fit these criteria of “exactness,” students who agreed or strongly agreed with the above statements most often cited lecture and/or ball-and-stick models, as well as molecular diagrams that they had seen throughout the course to date (note: these were predominantly Dash-Wedge, Newman, Fischer, and chair diagrams). In the excerpt

below, one student compares the use of manipulatives to constructing objects out of K'NEX®:

- Researcher: So, you believe a chemical model needs to be pretty close to the real thing in order to be considered a model?
- Nadine: It depends on what you're making [modeling].
- Researcher: OK...to what extent?
- Nadine: I mean...it depends...I guess if you're trying to show somebody something with a model...you can do like a blueprint kind of thing, like when you make a building or a castle out of K'NEX®.
- Researcher: OK...so...
- Nadine: But scale it. Like, a ball-and-stick...
- Researcher: Go ahead.
- Nadine: A ball-and-stick model has to be built correctly, like you have to follow the directions, like the K'NEX®, and if you didn't follow the directions, you wouldn't show the right information. It's [the ball-and-stick model] just bigger than it [what it represents].
- Researcher: So, there's one way to build it that is correct, except for the size issue?
- Nadine: Yeah.

This type of response, which was not an uncommon one (approximately 40% of participants made mention, specifically, of Legos® or K'NEX® being an exemplar of a

model akin to a concrete manipulative or diagram found in Organic Chemistry, for instance), is important for two reasons.

First, while concrete models and diagrams in chemistry *do* need to be exact in many ways (e.g., preserving the spatial arrangement of substituents as they would actually be found on the molecule), an over-exaggerated belief that this exactness causes there to be only a single correct way to construct a model is of concern. Previous research suggests that this observation may be linked to the fact that because novices tend to have a greater number of everyday experiences working with models and because everyday models *are* typically exact, they tend to transfer and ascribe this same property to scientific models, despite the fact that these models serve different purposes and tend to be more abstract in nature (Treagust et al., 2002).

This is not to say, however, that all students expressed a similar belief. One student in the current study reported, for instance, that “there is a lot more that goes into working with those models [ball-and-stick models], like you have to understand what’s possible and what’s not possible, and what [substituent] can go where and what effect that has if it’s in a specific place” (Student interview, Spring 2012). This type of more nuanced response indicates an awareness of the affordances *and* limitations of modeling in the context of Organic Chemistry – important distinctions that potentially allow novices to make more educated decisions regarding when and how to make use of models in the learning process.

Secondly, Nadine’s perception of chemical models as being near exact replicas of the phenomena they intend to depict coupled with her likening of model building in chemistry to constructing a model from a blueprint implies that some students may see

modeling in the field as a more algorithmic process rather than a dynamic one that requires not only understanding *how* to build accurate models but also what the *purpose(s)* of these models are. Throughout elements of this dissertation alone, students expressed reticence in constructing and/or manipulating models because they either did not understand what these models represented or because they thought the way the models were drawn or positioned by the researcher were the way they were “intended to be” (Student interview, Fall 2011). In these instances, greater exposure to various types of models in chemistry, such as physical manipulatives, and explicit explanation regarding the use(s) and dynamic nature of these models (and the molecules they represent) would appear beneficial to promoting students’ representational competence in the domain.

Analysis of survey and interview data also revealed that students found other characteristics of models equally as important. For instance, given that diagrams and concrete models represent visuospatial features of molecules, it was not surprising to subsequently find that 95.8% of students agreed that many models may be used to show different sides or shapes of an object (item MR/5), 97.2% agreed that models are used to physically or visually represent something (item MTV/27), and 86.6% agreed that models help create a picture in your mind of the scientific happening or object being modeled (item MTV/28). It is worth noting that because these latter two items factored out into their own scale on the MVM, it is likely that students in the study population perceive these features of models to be of great value. While I explore this possibility in detail in the third section of this analysis, it is important here to note that this finding is unanticipated given the categorization of Organic Chemistry as a spatially-complex field

(Harle & Towns, 2011). Additionally, it is plausible that high levels of agreement with items MR/5 and MTV/28 reflect the fact that many novices adopt imagistic strategies, such as mental modeling, when attempting to solve visuospatial tasks in the field (Stieff, 2007; Stieff et al., 2012). If this were the case, explicit illustration of the role models may have in supporting students' ability to "see" chemical phenomena (e.g., the shape and dynamic nature of molecules) is imperative in the teaching of Organic Chemistry.

Table 9.

My Views of Models (MVM) Survey Results

<i>Factor/Item No.</i>	<i>Item</i>	<i>M (SD)</i>	<i>%</i>		
			<i>Disagree*</i>	<i>Not Sure</i>	<i>Agree**</i>
MR/1	Many models may be used to express features of a chemistry phenomenon by showing different perspectives to view an object (such as a molecule).	4.24 (.71)	1.4	9.9	88.7
MR/2	Many models represent different versions of a phenomenon.	3.99 (.79)	4.9	16.2	78.9
MR/3	Models can show the relationship of ideas clearly.	3.97 (.89)	6.3	22.5	71.1
MR/4	Many models are used to reflect individual's different ideas on what things look like or how they work.	3.92 (.97)	9.9	16.9	73.3
MR/5	Many models may be used to show different sides or shapes of an object.	4.46 (.60)	0.7	3.5	95.8
MR/6	Many models in chemistry show different parts of an object or show the objects differently.	4.23 (.71)	2.1	9.9	88.0
MR/7	Many models in chemistry show how different information is used or integrated.	3.78 (.82)	5.6	26.8	67.6
MR/8	A model has what is needed to show or explain a chemical phenomenon.	3.13 (.98)	28.9	34.5	36.6
ER/9	A model should be an exact replica.	2.80 (1.05)	43.7	29.6	26.7
ER/10	A model needs to be close to the real thing.	3.67 (1.02)	16.2	16.9	66.9
ER/11	A model needs to be close to the real thing by being very exact, so nobody can disprove it.	2.82 (1.10)	41.6	28.2	30.3

ER/12	Everything about a model should reflect what it represents.	3.35 (1.14)	26.7	19.0	54.2
ER/13	A model needs to be close to the real thing by being very exact in every way except for size.	3.06 (1.18)	37.4	17.6	45.1
ER/14	A model needs to be close to the real thing by giving the correct information and showing what the object/phenomenon looks like.	4.00 (.91)	6.3	13.4	80.3
ER/15	A model shows what the real thing does and what it looks like.	3.47 (1.10)	21.1	20.4	58.5
ER/16	Models show a smaller scale size of something.	2.99 (1.30)	36.6	26.1	37.3
UM/17	Models are used to explain chemical phenomenon.	3.80 (.86)	7.0	25.4	67.6
UM/18	Models are used to show an idea.	4.15 (.80)	4.9	10.6	84.5
UM/19	A model can be a diagram, picture, graph, or photo.	4.15 (.84)	5.6	12.0	82.4
UM/20	A model can be an equation, such as a chemical reaction.	3.30 (1.20)	30.2	21.1	48.6
UM/21	Models are used to help formulate ideas and theories about chemical and scientific events.	4.00 (.77)	4.2	16.2	79.6
UM/22	Models are used to show how scientists apply models to scientific/chemical investigations.	3.87 (.88)	7.0	22.5	70.4
UM/23	Models are used to make and test predictions about a chemical/scientific event.	3.71 (1.06)	17.6	16.9	65.4
CNM/24	A model can change if new theories or evidence prove otherwise.	4.30 (.73)	3.5	5.6	90.9
CNM/25	A model can change if there are new advancements in the field.	4.43 (.68)	2.1	4.2	93.7

CNM/26	A model can change if there are changes in data or belief.	4.22 (.74)	3.5	7.7	88.7
MTV/27	Models are used to physically or visually represent something.	4.50 (.58)	0.7	2.1	97.2
MTV/28	Models help create a picture in your mind of the scientific happening or object being modeled.	4.30 (.83)	4.2	9.2	86.6
EUM/29	Experts do not need to use models, such as ball-and-stick models, because these models are too simple to explain the phenomena experts are interested in studying.	3.17 (.95)	14.8	21.8	63.4
EUM/30	Experts do not need to use models because they have enough knowledge in the field to solve questions without models being necessary.	3.76 (1.00)	10.6	17.6	71.8
MUC/31	Instruction on model use should be provided to students so that they understand how to construct and use models to solve problems in Organic Chemistry.	3.89 (.98)	12.0	11.3	76.8
MUC/32	Students should be permitted to use models on exams and other classroom assessments.	3.20 (1.3)	36.0	21.1	43.0
MUC/33	Since building models is time-consuming, students should be provided with time in class to work with models and see how this process connects to other learning strategies in the course. This should reduce the amount of time required to build models in the future.	3.50 (1.10)	21.8	22.5	55.6
DUM/34	Chemists use models to a greater degree than other scientists, such as biologists and physicists, because chemical phenomena cannot be seen by the naked eye.	3.12 (.78)	32.4	54.9	45.1

DUM/35	Biologists use fewer models because the processes studied by biologists exist at a macroscopic level (i.e., they are already easy to visualize).	2.57 (.70)	54.2	23.9	21.8
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In comparison, it was interesting to find that less than 50% of students perceived chemical equations and reaction mechanisms to be true models (item UM/20). The following two conversations represent why this might be the case:

Researcher: Umm, what about things like reaction mechanisms or chemical equations. Do you think they are or can be models?

Lydia: It could, yeah, I guess. I haven't thought about that as a model, but I guess it could concisely convey what's going on.

Researcher: So you think yes, if...

Lydia: Yeah, kind of, not as much. Not as much as that [a ball and-stick model]. Like, personally, that one is much more of a model.

Researcher: Why?

Lydia: Because, like, I can manipulate it more. It's more visual. It's not just symbols. It shows me what's actually going on.

Researcher: What about things like reaction mechanisms or chemical equations. Do you think those still count as models? And why, or why not?

Britney: Umm... I don't think those are so much models as, like, examp...like, if somebody were to like talk about a reaction and

then like show the reaction, I think that would be just an example of something.

Britney: It's not like, uh, an exact model. It's just an example of what the reaction is doing.

Though chemical equations are considered, at least by some, to be predictive models (Laszlo, 2011), it is evident that students either see them as separate entities or are unsure how to classify them. Consistent with earlier survey findings, the rationales Lydia and Britney provide for categorizing chemical equations and reaction mechanisms in the above manner suggest that descriptors such as “exact,” “visual,” and “manipulatory” do not pertain to these visualizations, and, therefore, they cannot be models. In Treagust and colleague's (2002) study, the authors note that

[survey] results distinguish two types of models: the scale replica, a precise representation, which has accuracy and detail; and the imprecise representation, which doesn't have the accuracy or detail, and may be nothing like the object, but can provide insight into why and how something works the way it does. (p. 364)

It is likely, in the present study, that students are referring to this distinction. The chemical equation or mechanism is symbolic in nature and thus more abstract than the physical models students frequently encounter in the classroom (although they encounter both). In addition, the alphanumeric script used in these equations, while common to the

field, do not illustrate either the features of the atoms and molecules they represent or the interaction between these atoms and molecules, though it is implied.

It is interesting to note, furthermore, that the characteristics Lydia and Britney identify as constituting “model-ness” are all typical features of physical models (such as the ball-and-stick model). Because students in this study population were *explicitly* introduced to concrete manipulatives and some of the potential functions of these models in their Organic Chemistry I course, this observation may indicate, alternatively, that students lack pre-formed opinions about whether chemical mechanisms and equations are models. Instead, they come to rely on familiar characteristics of what they *do* consider a model to be (in this case, characteristics of ball-and-stick models) as a referent for evaluating whether or not other visualizations in the field are, indeed, also potential models.

While the central focus of this dissertation is *not* on students’ understanding of chemical equations and/or reaction mechanisms, the above findings collectively suggest that it is important to acknowledge that novices’ broader understanding of the role of visualizations in Organic Chemistry and the relationships between these visualizations appears to be greatly influenced by the types of models explicitly identified for them by the instructor and the ways in which these visualizations are described as being useful for learning in the field. In the semester this survey was conducted, for instance, students were asked to take part in an exercise where they were encouraged to predict and construct the product(s) of a series of alkane reactions using concrete models. This activity was designed as an extension of the representational translation task assessment discussed in Chapter 4. Preliminary findings revealed that few students elected to

construct concrete models because they felt they did not require these models in order to successfully complete the tasks or because concrete models did not appear applicable to solving tasks of this nature. The latter half of this statement suggests that, although certain types of models *do* have very specific applications in the discipline, students may hold an overly constrained view of these uses due to the limited experiences they have working with models in educational settings.

Despite this, it was heartening to see that 78.9% of students agreed on the survey, for instance, that many models represent different versions/characteristics of a phenomenon (item MR/2), and 67.6% agreed that models are used to explain chemical phenomena (item UM/17). The narrative excerpt below, in which a student explains why she strongly agreed with these items, provides an indication of how this population might view models as relevant to learning in Organic Chemistry:

Researcher: Can you tell or show me in what ways models illustrate or explain various aspects of a chemical phenomenon?

Kelly: Well...like...a Newman [projection]. You can use the diagram or the concrete model to show various conformations of the molecule. But this also tells you about the energy level of the molecule... high or low.

Researcher: About the stability of the molecule?

Kelly: Yeah. For me, it's easier to see it [the interactions between substituents] on the diagram, but the model is easier to rotate, so

you can see it that way, too, and actually look straight down it [the central bond].

Researcher: What do you mean by that?

Kelly: So, I...use the model to tell me where substituents go and then look at the diagram to figure out if it's high or low energy conformation. Yeah.

In a practical sense, these data arguably demonstrate that students are aware of the multiple forms models may take in the discipline, the unique purposes they may have for each individual, and the ways multiple visualizations can be integrated in order to generate a better understanding of a chemical phenomenon or principle. Recognition of these important features of models is central to the development of one's representational competence in the domain (Kozma & Russell, 1997).

From a broader perspective, research has also shown that presenting information in multiple modalities, including the use of diagrams, text, and physical manipulatives, can be particularly advantageous to students who are actively attempting to assimilate and interpret such information (Ainsworth, 2006). This cognitive theory of multimedia learning—as it came to be known—has not only aided researchers in identifying the importance of how learners come to construct integrated representations (Mayer, 1997) but also how, even at the mental model level, students generate “complementary representations that can communicate with one another” (Schnotz and Bannert, 2003; as cited in Ainsworth, 2006, p. 184). It is this latter finding that is most closely reflected in Kelly's comment above. However, ongoing research efforts in the chemistry education

community have continued to identify the importance of multimedia learning in promoting students' development of representational competence in the domain (see, as example, Kumi et al., 2013).

Promisingly, survey results also showed that more than 65% of students agreed that models could be used both to make or test predictions and to formulate new theories (items UM/21, 23). While this means that 35% of participants either were not sure or disagreed with this perception, these results are indicative that students generally hold or are in the process of developing more sophisticated views about models in the context of Organic Chemistry. This is contrary to previous reports by Treagust and colleagues (2002) and Grosslight and colleagues (1991) in which more than 50% of secondary students in each study were shown to lack an understanding of how models could be used as tools for conducting inquiry.

Almost all students (>90%) were aware, though, that these models could change as a result of new evidence (item CNM/24) or new advancements (item CNM/25) in the field. One student, for instance, mentioned that as virtual modeling technologies improved, it might be “easier to use those [virtual] technologies to translate between representations than a ball-and-stick model, which is very time consuming” (Student interview, Spring 2012). This is reflective of an appreciation that science is a process rather than a series of unquestionable and unchanging facts. Given previous empirical research indicating that even high-school, upperclassmen chemistry students struggle with this concept (Boo, 1998), these findings highlight a unique characteristic of the Organic Chemistry I students in this study, perhaps resultant from a greater focus on evidence-based reasoning in university settings as opposed to high-school classrooms.

Exploring students' perceptions of model use by experts inside and outside the field. Examine any research notebook or laboratory space and you will find that representations and other forms of visualization are used pervasively by experts to depict and communicate important knowledge about the chemical world (Kozma et al., 2000). Though these same practices are often translated into the classroom, research suggests that this process occurs in inconsistent ways that result in visualizations being presented as static entities devoid of any historical context or significance (Treagust et al., 2002). For this reason, I was curious to what extent the novice students in the current study were aware of the broader role models and representations have in the field, or whether they perceived these visualizations to only be of use to individuals entering the discipline for the first time.

Consistent with previous research (Treagust et al., 2002), the majority of students believed expert chemists had no need to make use of models. Approximately 72% agreed, for instance, that “Experts [did] not need to use models because they [had] enough knowledge in the field to solve questions without models (e.g., ball-and-stick models) being necessary.” When probed further about these beliefs during follow-up interviews, students also commonly reported that they felt models, such as the ball-and-stick models they were exposed to in their Organic Chemistry course, were too simplistic to be able to capture the complexity of the phenomena chemists were interested in studying. The exchange below is a classic exemplar of this:

Researcher: Can you tell me briefly about how you think experts—so, chemists in the field or professors here who do research, for instance—make use of models.

Matthew: I don't think they necessarily do. I mean, I think they just know what it is they're studying, and they know...have...resources, like books, to figure out the information they need, so they don't use models like the ones we have [the ball-and-stick models].

Researcher: Do you think they would use models if the thing they were studying were really complex? Like, would that help them “see” the problem better?

Matthew: Maybe, but I think it would become confusing after a point. Like, the model itself would become too complicated.

For students such as Matthew, beliefs about how experts use models in the field are likely shaped by one of two factors. First, as novices in the discipline, students have limited exposure both to the types of models employed by Organic Chemists as well as to practicing chemists themselves (Samarapungavan, Westby, & Bodner, 2006). This could presumably lead students to develop perceptions of models and modeling that are restricted to and contextually constrained by the way(s) in which they have seen models used by faculty in the classroom. However, because this experience is likely true of many, if not all, students taking part in a first-semester, introductory Organic Chemistry course, this rationale seems insufficient to account entirely for the above findings.

Instead, it is probable that students who either agreed or strongly agreed with statements on the EUM scale also held naïve epistemologies of models, as measured by other items on the MVM survey. For instance, Matthew’s belief that models would “become confusing after a point” may be resultant from a linked perception that models must be near exact replicas of the phenomena they intend to represent (which he agreed with). It would not be surprising, then, for him to report that experts in the field do not make use of models because as the complexity and abstractness of the phenomenon increased, the ease with which experts could construct and use models, at least according to his view, would decrease. In other words, there would be a threshold at which the cost of modeling would outweigh any benefits associated with doing so.

Regardless, it is promising that approximately 30% of participants did indeed recognize that models were of value to experts throughout the discipline. When asked to explain why they believed this to be true, almost all participants (98%) referenced Watson and Crick’s model of the DNA double helix as an example of how models had been used, historically, to advance scientific knowledge, including the fact that construction of this model was a joint effort between many researchers. These participants were also more likely than their peers to note that the abstractness of the phenomenon being modeled was irrelevant because chemists had access to “virtual programs and models” that could “accommodate for this abstractness.” One student went so far as to suggest that “models [were] especially necessary in those cases because it was harder to envision what the phenomenon looked like” (Student interview, Spring 2012). These data indicate that students in this cohort may be more aware of both the malleable and explanatory nature of models than participants in the majority, and that their beliefs

about models may increasingly begin to approximate those views more commonly held by experts in the field (Grosslight et al., 1991). However, due to the manner in which the study was conducted, it is unclear who these students were (e.g., high- vs. low-spatial students, students with previous high school science modeling experience).

In considering the broader uses of models across scientific disciplines, data show that less than 50% of the students surveyed believed models were used more frequently by chemists than by other scientists (e.g., biologists and physicists). However, nearly 55% of students were not sure, for instance, if “chemists used models to a greater degree than other scientists, such as biologists and physicists, because chemical phenomena cannot be seen by the naked eye” (item DUM/34). These findings suggest that while students possess a certain degree of global awareness about the role of visualizations in the scientific community, they may sometimes be unaware of the reasons behind why these models were constructed. Said a different way, students know that models exist but may not necessarily understand what meaning these tools have for experts either in Organic Chemistry or in related fields. Greater intradisciplinary attention to and discussion of the importance of models in textbook readings and in the classroom are two potential solutions to address this concern.

It is also necessary to keep in mind that a large number of students traditionally enrolling in Organic Chemistry courses at Andrews University, including those taking part in the current study, are *not* majoring in chemistry. Instead, as is common nationwide, Organic Chemistry has a dual function in serving as a gateway course for students completing pre-professional health programs or degree programs in biology, biochemistry, and other related fields (Pursell, 2011). There are two important

ramifications of this practice. First, as educators, we must be conscious that *interdisciplinary* conversation regarding the use of scientific visualizations is also a necessity. Secondly, and as a likely result of that conversation, we would be well-advised to make analogous use of the same types of representations, physical models, and other forms of visualization across scientific disciplines in an effort to uniformly promote students' development of representational competence.

Students' views on the use of concrete models to solve Representational Translation Tasks in Organic Chemistry are positive but constrained by classroom practice. While the above findings serve to detail the general perceptions students hold of models and modeling in Organic Chemistry, they do not provide specific insight into the role students perceive models may have in supporting their ability to understand the relationship between the two-dimensional depiction of a molecule and the 3D entity it represents or their ability to translate between various 2D diagrams in the field. To address this concern, and to corroborate and expand upon interview findings in Chapter 4, students taking part in the follow-up, semi-structured interviews were asked to respond to three tasks. First, participants were asked to interpret the conventions of a Dash-Wedge, Newman, and Fischer diagram of a given molecule. Second, participants were provided with a ball-and-stick model of this molecule and asked to describe what information the model provided above and beyond what was depicted in the 2D diagrams they had been shown previously. Lastly, participants were prompted to briefly indicate whether or not they believed models were useful for solving representational translation tasks, and the rationale for this response.

Descriptive interpretive analysis (Smith et al., 1995) of participants' responses to the first task revealed that the majority of students (98%) possessed a thorough understanding of the conventions of the Dash-Wedge and Newman diagrams. However, slightly more than one-third of these students (35%) had difficulty articulating the conventions of the Fischer projection. The following narrative is illustrative of typical researcher-student dialogue around this topic:

Researcher [1]: Okay, so here is a Dash-Wedge diagram of a particular molecule.⁴ Can you describe for me what information is present in this diagram...what this diagram tells or shows you about the molecule.

Maggie [2]: So, the solid lines show me that the methyl and ethyl groups are in the plane of the page. The two hydrogens are coming out of the page because they are on wedges, and the -OH and -NH₂ groups are going into the page because they are attached to the dashed lines.

Researcher [3]: Excellent!

Researcher [4]: What about if I show the molecule to you as a Newman projection?

Maggie [5]: Well, I see the Newman projection as a Dash-Wedge

⁴ Note: The first molecule in the RTT was used for this task and translated into all 3 diagrams. Students taking part in this study had not previously completed the RTT; thus, these diagrams were new to them.

rotated 90° , so the two pretty much tell me the same kinds of things.

Researcher [6]: You mean, like where certain substituents are located in relation to one another?

Maggie [7]: Yeah, stuff like that. This diagram is also in a stable conformation because it's staggered and the methyl and ethyl groups are opposite one another [student points to methyl/ethyl groups on molecule].

Researcher [8]: Why's that important?

Maggie [9]: Because it minimizes steric interaction between the two groups.

Maggie [10]: At least that's what we learned in class.

Researcher [11]: Sounds reasonable.

Researcher [12]: Alright. Last one. What about the Fischer projection? [places diagrams in front of student]

Maggie [13]: Umm... well... we didn't really spend much time on the Fischer projection. I think I remember that these top two substituents [points to the substituents on the top, horizontal arm of the Fischer projection] come out of the page, while the bottom two [points to the substituents on the bottom, horizontal arm of the Fischer projection] go into the page.

Researcher [14]: What about these guys [substituents] on the vertical axis?

- Maggie [15]: In the plane of the page?
- Researcher [16]: Mmm...not quite.
- Researcher [17]: This is going to sound weird, but draw a bowtie at the point where the vertical and horizontal axes cross, like this [draws one as example]. See how the bowtie looks like a wedge? This will remind you that the substituents on the horizontal arms of the Fischer are coming out of the plane of the page. The substituents on the vertical axis go into the page. Remember that you can also try to assign R/S stereochemistry to the Fischer like Dr. Brown taught you. This may help you understand the spatial relationship between the different substituents.
- Maggie [18]: Okay, that makes sense. So the “arms” are coming out of the plane of the page and the top and the bottom go into the page.
- Researcher [19]: You got it.

There are two key points to be gleaned from this conversation. First, while it is clear that students are familiar with the conventions of both the Dash-Wedge diagram and Newman projection, it is not clear in all cases whether this familiarity reflects a deeper, structural understanding of these representations or if students are simply regurgitating superficial information transmitted to them by the teacher. Lines 14 – 18 above, in which the student mentions that the Newman projection depicts a stable conformation of the

molecule because it is in a staggered conformation that contains the least amount of steric interaction among substituents, are a prime example of this. Within the context of the Organic Chemistry course in which these students are enrolled, though, these ambiguous moments are not necessarily problematic because the above student is accurately recalling information that will likely be assessed at some point in the course. However, from a broader practical standpoint, a purely definitional understanding of these representations will likely result in student failure when it comes to manipulating and selecting an appropriate diagram for a given task, particularly on problems requiring students to apply and synthesize knowledge. Likewise, while students may be successful at performing one task even if they possess only a basic comprehension of the diagrammatic conventions evidenced in the task, there is no guarantee that they will possess sufficient representational competence to accurately complete alternate tasks that require them to transfer knowledge from that familiar context to a novel context (Okanlawon, 2008). It is arguable, in that case, that no true learning has occurred.

A second important point ascertained from the above discussion, and consistent with those findings presented in Chapter 4, is that students have a more limited understanding of the Fischer projection than of the other diagrams presented in the study, not because they lack exposure to the Fischer projection in class, but rather because the conventions of the diagram itself are confusing to them. This is exacerbated by the fact, for instance, that the solid lines in a Fischer projection are not equivalent to the solid lines found in a Dash-Wedge diagram, nor do they innately illustrate the three-dimensional properties of the molecule. Research has shown that providing students with access to concrete models that represent molecules in the form of a Fischer projection may help

them to better understand this diagram because students can physically “see” the three-dimensionality of the molecule (Stull et al., 2012). However, because models are not always present in the students’ learning environment, even relatively crude strategies, such as the bowtie trick, may be successful at conveying to students the spatial relationships inherent of the Fischer projection.

At the other extreme, consistently allowing students the opportunity to work with models does not predicate that they are aware of how to do so in meaningful ways to solve discipline-specific tasks. When students were subsequently presented with ball-and-stick models in the second prompt, for instance, it became immediately evident that some had experience working with this type of model previously and others did not. Those that self-reported that they *had* worked with concrete manipulatives prior to this study (about 20% of participants) were quick to note that performing sigma bond (i.e., internal) rotations with the model allowed for easy translation between the Dash-Wedge, Newman, and Fischer diagrams, and that the tangible nature of the model, as one student put it, “reduces the stress of having to imagine everything in three dimensions in your head” (Student interview, Fall 2012) (Table 10). Given that a large percentage of students resort to spatial-imagistic strategies when problem-solving in the domain despite the fact that they are, at times, error-prone (Stieff et al., 2010), this affordance is both noteworthy and potentially advantageous for student learning. If nothing else, it is clear that the models allowed these students to more readily comprehend and visualize the spatial nature of molecules.

In comparison, those participants who self-reported having limited or no previous experience using ball-and-stick models often stated that these manipulatives were of no

additional value to them either because it was unclear how one built a model to match what was shown in the 2D diagram or because faculty did not allow students to use these models in class. Some participants also reported that using more algorithmic approaches to understanding and translating between diagrams, such as assigning R/S stereochemistry to Fischer projections, were more efficient than spending time building a model and ensuring that it was an accurate representation of the molecule it intended to depict (see Table 10). I found it interesting that many of the reasons provided by these students appeared to be framed by their exposure to and use of models in the classroom, and so I inquired as to whether or not students would find models more informative and useful if their teacher encouraged the use of models more in the process of learning Organic Chemistry. Promisingly, the majority of students (~85%) responded that they possibly or definitely would because this would provide them with a context in which to “learn more about what the balls and sticks actually are supposed to be and what purpose they have” rather than seeing the modeling kit as a “waste of \$40 in the bookstore” (Student interviews, Fall 2012).

Table 10.

Positive and Negative Attributes of and Reasons for Using or Not Using Concrete Models

Rationale for Using Models:	% Participants indicating Response
(A) Models provide more visuospatial information about a molecule than is shown in a 2D representation	76%
(B) Physical models are tangible, hands-on tactile instruments that aid in problem-solving	54%
Rationale for Not Using Models:	% Participants indicating Response
(A) Constructing and using models is time-consuming/not permitted in class	61%
(B) The conventions of models are confusing	9%
(C) No instruction in model building and/or use is provided by the teacher	39%
(D) Utilizing problem-solving heuristics is more efficient than working with models	24%

With specific regard to the role of models in performing representational translation tasks, many of the responses obtained from students were identical to the patterns emergent above. Participants who were more familiar with concrete models again capitalized upon the fact that it was easier to perform internal, sigma-bond rotations using these models, allowing for straightforward, step-by-step conversion between the various representations of a molecule. In contrast, several students ($n = 14$ of 48) noted that it could sometimes be difficult to determine what perspective one should adopt when viewing the model (if the model was already provided pre-constructed, as was the case in

this portion of the interview) and that this commonly led to holistic manipulations of the model that served no functional value for solving the task.

Training students to use models for the purpose of solving RTTs may help abrogate this latter issue (Padalkar & Hegarty, 2012; Stieff, Scopelitis, et al., in preparation). For instance, Padalkar and Hegarty (2012) conducted a quasi-experimental study in which 54 students were assigned randomly either to a control condition or an experimental condition in which models-based feedback was provided. Participants in both groups were first asked to solve a series of representational translation tasks using concrete models, if they so desired. While participants in the control condition were then given a break, participants in the experimental group were prompted to align the provided models to their respective solutions as a check. Note that this task is impossible to achieve if the student's solution is not a correct conformer of the initial diagram presented in the RTT. Students who discovered that the model did not match their solution were provided with additional instruction and opportunities to correct their initial response.

Following the training interval, students in both cohorts were asked to complete a series of post-test and transfer tasks, again with models being present for use. Results demonstrated that the experimental group significantly outperformed the control group on these tasks, likely, the authors argue, because the intervention led students in the experimental group to develop a better understanding of how concrete models could be used to solve RTTs. While I remain reserved that direct training of this nature conditions students to solve representational translation tasks without promoting true understanding and learning, these findings show that a greater focus on and commitment to the use of

models as problem-solving tools in the Organic Chemistry classroom may be of great value to students as they begin their studies in the discipline.

Summary of Findings, Limitations, and Future Directions

This exploratory study sought to unearth, in greater detail, the perceptions students held of models and modeling in Organic Chemistry, including the potential mediating role models had in improving student performance on representational translation tasks and their beliefs about how models were used by the scientific community. Consistent with my initial hypothesis, analysis of participant survey and interview data revealed that a number of students held naïve realist epistemologies of models in which these visualizations were primarily seen as immutable or near-exact replicas of the phenomenon they were intended to depict. This finding is in agreement with previous reports in the field (Grosslight et al., 1991).

While this was the case, it was also clear that several students held more advanced and nuanced views of models that began to approximate those commonly reported by experts in the field (van Driel & Verloop, 2002). These views included describing models as having the capacity to represent more abstract phenomena, as well as definitively making mention of the predictive and explanatory nature of models, among others. This latter finding, in particular, suggests that secondary and post-secondary education may be a period of transition for many students. Indeed, research argues that college-level classes in Organic Chemistry should promote the application of course material over rote factual memorization because this allows students to draw deeper connections to the content they are studying (Mullins, 2008). In the context of the

research presented here, such pedagogical practice could have the potential to advance students' representational competency beyond the superficial degree of understanding ascribed to novices by Kozma and Russell (2005). In short, it is clear, then, that while much of the earlier work in this field has focused on students' perceptions of models and modeling in the K-12 arena (Grosslight et al., 1991; Treagust et al., 2002, 2004), significant attention need be placed on the substance of how (and why) students interact with models in university settings.

Analysis of semi-structured interview data regarding students' perceptions of concrete models as tools for solving representational translation tasks in Organic Chemistry reaffirms this need. While previous empirical evidence (Stull et al., 2012), including data presented in earlier chapters of this dissertation, would suggest that models serve as an affordance for enhancing students' ability to perform these tasks, it is clear from student narratives that these models appear, in many ways, inaccessible. Most of the emergent themes obtained from these interviews—limited time to construct and work with models, no instruction on how to use models, restricted use of models on in-class examinations, etc.—mirror recent and preliminary reports from similar studies in the field (Stieff, Scopelitis, et al., in preparation; Stull et al., 2012), suggesting that these beliefs may be endemic of students across varied classroom settings rather than unique to the population of students taking part in the current study.

More importantly, these results illustrate that students' perceptions of models and modeling in Organic Chemistry are framed almost uniquely by their *practical* classroom experiences. This being the case, there are two possible avenues through which faculty can promote positive (i.e., expert-level) perceptions of models. First, faculty can

incorporate more models-based classroom instruction into their repertoire. In their phenomenological study of prospective *gymnasium* teachers perceptions of teaching and learning in chemistry, Koballa et al. (2000) show, for instance, that such practices are utilized by instructors to situate learning as an active process that allows learners to construct new understandings for themselves. Second, faculty can provide students with more out-of-class opportunities to utilize models and/or view chemists working with models in research settings. This would serve to highlight the practical uses of models and allow students to connect their knowledge of modeling in the chemistry classroom to real-world applications, which they sometimes saw as disconnected (see students' views of expert use of models above). While I have presented these recommendations separately, it is important to acknowledge that, in truth, both should be implemented *in tandem*, as the goal in both cases is to ultimately increase students' exposure to models in the context of Organic Chemistry.

Despite these recommendations and the results reported herein, however, a significant amount of further research is necessary to fully and accurately portray the rich complexity of students' perceptions of models and modeling in Organic Chemistry. The present study, for instance, only focuses on students enrolled in an Organic Chemistry I course at Andrews University, a doctoral degree-granting institution. It might be of interest and value, therefore, to conduct a larger-scale study of both novice and advanced (e.g., graduate) students' perceptions of models across a number of educational contexts, including liberal arts colleges, comprehensive institutions, and community colleges. Additionally, none of the current perceptual studies in this area have examined the relationship between student demographic variables, such as level of spatial ability, and

perceptions of models and modeling in Organic Chemistry, though these variables have been shown to have a tremendous impact on how students make use of models to solve visuospatial tasks in the domain (Pribyl & Bodner, 1987; Stieff et al., 2012; Stull et al., 2012). I would argue that it is imperative that these variables be taken into consideration because there is a high likelihood that they may serve as confounding factors that contribute to the overall perceptions students hold of models in the field. Lastly, and from a methodological standpoint, while the MVM survey used in this study improves upon earlier instruments described in the literature (Grosslight et al., 1991; Treagust et al., 2002), there is still a significant need to develop valid and reliable measures of students' understanding of models in contexts such as the one described here.

CHAPTER 6: FACULTY PERCEPTIONS OF MODELS AND MODELING IN ORGANIC CHEMISTRY AND IN CLASSROOM INSTRUCTION

Introduction

It is clear from the preceding chapter that students' perceptions of models and modeling in Organic Chemistry are heavily shaped by the types of classroom experiences they engage in, including their interactions with faculty in these contexts. While many students were seen to hold rather nuanced views of chemical representations and models, a significant number still retained naïve realist epistemologies of chemistry visualizations consistent with previous reports in the field (Grosslight et al., 1991; Treagust et al., 2002). Furthermore, students were often unaware of the broader implications models had in the discipline (e.g., for purposes of scientific communication by experts), reaffirming that their views of modeling may be constrained by and limited to the modeling practices they witness and engage in within the classroom. In an effort to account for these observations, I argue that it is imperative to consider not only *what* is going on in the classroom from an instructional standpoint, but also faculty's beliefs regarding models and modeling, as these perceptions likely mediate the degree to which faculty enact a models-based pedagogical approach. Research suggests that attending to these elements of faculty's practical knowledge (van Driel & Verloop, 1999) is of particular importance because while many instructors may report that models are valuable both in a professional and in an instructional sense, the ways in which they engage in modeling practices in the classroom is often inconsistent with these beliefs, leading students to

perceive these tools to be of little use in their study of science (Harrison, 2001; Justi & Gilbert, 2002a; van Driel & Verloop, 1999, 2002).

In their qualitative study of 87 in-service science teachers' knowledge of models and modeling in science, van Driel and Verloop (1999) stated, for instance, that while teachers shared a general notion that models were simplified representations of reality, they often "emphasized different functions and characteristics of models" (p. 1150). Interestingly, these characteristics rarely included the predictive or explanatory nature of models, or the fact that models could be utilized in the process of constructing new knowledge (whether globally or for the individual learner), despite these functions being highly valued by expert chemists. From a practical standpoint, the authors argued that this inconsistency results in students having limited opportunities to construct their own models, test pre-constructed models, and understand the benefits afforded by having access to these tools.

In a similar study, Harrison (2001) conducted qualitative interviews with 22 pre-service and expert science teachers to elicit information about their views of modeling and use of models in the classroom. Descriptive analysis of interview transcripts revealed that these teachers, collectively, held a view of modeling that was consistent with reported best practices for model use in the literature. However, on an individual level, more than half of the teachers interviewed displayed varying and discrepant levels of modeling knowledge. In addition, the degree to which teachers made use of models in the classroom appeared to be correlated less with their attitude towards modeling and more with their subject area of expertise. Physics teachers were identified as being the most creative and consistent in their use of models, for instance, while chemistry teachers

were found to be the least consistent. Specifically, the author reported that chemistry teachers “repertoire of model-use contrasted notably with the plethora of models found in their textbooks” (Harrison, 2001, as cited in van Driel & Verloop, 1999, p. 1256). This latter finding is particularly troublesome, as it indicates an area where students may potentially develop misconceptions regarding the relationship between the representations, models, and other forms of visualization they encounter across a wide array of media.

Regardless, while these studies have illustrated the potential effects classroom context and faculty perceptions of models and modeling can have on novices’ representational competence in scientific domains—including their perceptions about and uses of concrete models—they have not focused extensively on tertiary-level instructors and instruction in Organic Chemistry. The small-scale, exploratory study described below seeks to respond to this concern. Using a mixed methods approach combining both classroom observation and semi-structured interview techniques, I addressed the following questions:

- 1. What perceptions do faculty hold of models and modeling in Organic Chemistry?**
- 2. How do faculty make use of concrete models during instructional episodes related to the teaching of 2D molecular representations and the subsequent steps necessary to translate between these representations?**
- 3. According to faculty, what obstacles might hinder them from integrating concrete models effectively into their pedagogical repertoire?**

I hypothesized that faculty would not only hold positive and sophisticated views of models, but also report finding value in using specific models, such as lecture and/or ball-and-stick models, as part of their instructional practice, especially given that they have had multiple opportunities to witness the affordances models provide both in classroom settings as well as in the professional arena. However, as previous empirical evidence suggests (Harrison, 2001; Justi & Gilbert, 2001), it is likely that these perceptions will manifest in the classroom in unique and possibly contrasting ways.

Description of Participants

This study was conducted with three Organic Chemistry I faculty at Andrews University. Dr. Petrosian completed his doctoral work in Biochemistry and has been teaching Organic Chemistry for more than 40 years. Dr. Roberts completed his doctoral degree in Chemistry and has been teaching in the field for approximately 25 years. Professor (Prof.) Cooper is currently completing his doctoral degree in Chemistry and has taught Organic Chemistry for 2 years. All faculty are responsible for both teaching and performing research at the university. While Profs. Petrosian and Cooper primarily teach the lecture and discussion portions of the course (n = 250 students/ea. per lecture section), Dr. Roberts traditionally has taught the laboratory component. In the semester this study was conducted, however, Dr. Roberts was teaching both lecture and laboratory sections of Organic Chemistry I. All faculty took part in both the interview and classroom observation phases of the study. In every case, interviews were conducted following classroom observations to reduce the chance that these discussions would bias faculty's instructional practice (e.g., faculty would try to incorporate models into their teaching

when they typically did not). Faculty were not compensated for their participation in the study, as recommended by the university's Institutional Review Board.

Results and Discussion

Concurrent descriptive interpretive analysis (Smith et al., 1995) of faculty interview and classroom observation data resulted in the emergence of three core elements. These included: (a) *faculty possessing positive views of models in the field but mixed views of modeling in the classroom*; (b) *faculty engaging in modeling-based instructional practices that do not appear to promote students' development of representational competency in the domain*; and (c) *faculty beliefs about best modeling practices in the classroom as a result of reflective practice vs. attending professional development seminars*. Each of these themes, which align respectively with the above research questions, is discussed below.

Faculty perceptions of the use of models in the classroom and in the field.

Research suggests that experts' use of diagrams and concrete models in the laboratory and in the classroom is both ubiquitous and seamless, with these representations serving important functions in conveying and communicating knowledge about the chemical world (Kozma et al., 2000; van Driel, 1998; van Driel & Verloop, 2002). Accordingly, I found it necessary to begin by asking faculty to describe their perceptions of these visualizations and to discuss the role models, in particular, had in the field and in academic settings. This conversation was intended not only to identify what features of diagrams and models faculty perceived to be most (or least) noteworthy, but also to

examine what similarities and differences existed in faculty's views of chemical visualizations across contexts, as this could likely have critical implications for how students develop representational competence in the domain.

Collectively, faculty reported finding value in using multiple forms of representation in their own work, including both diagrams and concrete models, because these representations often possessed complementary features or properties. Dr. Petrosian stated, for instance, that:

Working with representations and models in chemistry is extremely important. There are some topics you simply cannot understand without using concrete models; stereochemistry, for instance. A 2D Newman diagram might help you explain the energy state of a molecule, but building a model might help you more easily predict and see why this is the case. You can *see* [his emphasis] what types of steric interaction might exist by physically rotating the molecule. That's easier than trying to imagine it in your mind.

Dr. Petrosian's attention to the predictive and explanatory nature of models is consistent with previous reports examining experts' perceptions of models in the field (Kozma, 2000; Kozma et al., 2000; Schwartz et al., 2007), and reifies an important role for models in bringing unseen chemical phenomena to life. Furthermore, his emphasis on constructing models when attempting to make meaning of novel situations or processes signifies a sophisticated understanding of the potential affordances garnered from these manipulatives, namely that models can be used to test ideas—even those that are initially

abstract or unknown in nature. As evidenced in the survey data found in the preceding chapter, this affordance is, at times, lost on students, possibly because the types of experiences they are asked to participate in do not require them to utilize models in that way. It appears clear, therefore, that in order to promote higher levels of representational competence in our students, we must explicitly *show* them that concrete models possess critical features that are capable of accomplishing these deeper procedural needs, perhaps through engaging students in using models to solve real-world, complex problems (e.g., constructing various isomers of familiar molecules, such as glucose).

Consistent with previous research (Kozma, 2000; van Driel, 1998; van Driel & Verloop, 2002), faculty also suggested that models possessed an integral role in communicating knowledge about the chemical world. Professor Cooper reported, for instance, that:

Models and 2D diagrams are an important part of my research as an Organic Chemist. I am constantly encountering [he mentions that these encounters are primarily in the literature] novel representations as I go about my research, and I have to learn to efficiently interpret and use these representations [for the purposes of his own research] based on what they tell me about the types of information already known in the field.

When asked to discuss further his own contribution to the ongoing conversation about chemical phenomena via the use of visualizations, Prof. Cooper mentioned that he “also had an important role and obligation in sharing the findings of his research with

others...it's something expected in [our] field.” This commentary illustrates, importantly, that the dissemination of knowledge regarding the chemical world, including the use of visualizations to depict this knowledge, is common practice in chemistry, and that the provision of a space to share this knowledge is necessary for further advancement in the field.

In comparison, however, faculty's perceptions of models in classroom contexts were mixed. Consider the following exchange:

Researcher: Can you tell me a bit about what role you see concrete models having in supporting students' understanding of 2D representations in chemistry.

Dr. Roberts: Certainly, they can be helpful, but when [I] learned Organic Chemistry, we didn't have detailed structures or these fancy models as back-ups or as illustrations. We learned it.

Dr. Roberts: We learned it because we had good teachers and good professors.

Researcher: Okay.

Dr. Roberts: Again, modeling is very important, but nothing replaces a good explanation and good instruction in the classroom.

In this scenario, terms such as “illustration” and “back-up” tend to convey the notion that models are seen as secondary features in the learning environment, rather than as true affordances enmeshed in these contexts as part of a pedagogical approach designed to support student learning and students' understanding of molecular diagrams. The notion

that “good” instruction could suffice, all else withstanding, is also troublesome and ambiguous. When asked to elaborate upon this point, Dr. Roberts commented that “good teaching leads to learning.” It is unclear, still, exactly what this response was intended to convey, though it insinuates, perhaps unknowingly, that concrete models *cannot* promote learning. In light of the multifaceted and varying definitions of good teaching found in the literature (Fenstermacher & Richardson, 2005), this observation also suggests that faculty may rely upon intuitive ideas of what quality teaching “looks like” and are perhaps unaware, at least in some respects, of what pedagogical practices constitute good teaching in their field.

Alternatively, the above exchange with Dr. Roberts could reflect a broader issue related to his identity in the classroom. In other words, it may very well be the case that Dr. Roberts believes that since *he* learned Organic Chemistry in a traditional (i.e., non-models based) instructional format, and since he has been teaching this way for the last decade or more with relative success, that this *is* the correct way to teach. Admitting otherwise would give the impression that his practice is flawed and that he is a “bad” teacher—both threats to his identity as an educator (Rogers, 2003; Stolk, Bulte, De Jong, & Pilot, 2009).

Regardless, the fact that this type of response was not uncommon among the other faculty in this study is potentially cause for even greater concern. Dr. Petrosian and Prof. Cooper also both indicated that models were not a necessity in the classroom. Prof. Cooper reported, for instance, that “providing students with an opportunity to use models on exams and other assessments would only ‘slow students down’ because a lot of them don’t know how to use models.” While constructing models can indeed be a time-

consuming task, the latter half of this comment is particularly worrisome because it presents students in a deficit light – one in which *all* students are potentially seen as being incapable of or lacking the skills necessary to make meaning of these tools and manipulate them for various purposes, such as problem-solving, in the domain. A myriad of previous empirical studies (Oke & Alam, 2010; Stull et al., 2012; Wu et al., 2001), including data presented in earlier chapters of this dissertation, show that this argument is presumptive.

Despite this, it is important to note that faculty did not completely discredit the role concrete models could have in teaching and learning. Dr. Petrosian believed, for instance, that students would prefer and even enjoy working with models in class or recitation because of their physical nature and suggested that textbook publishers could go so far as to package molecular modeling kits with texts to “encourage [students’] use of models.” He was cautious to mention, though, that students should not come to rely upon these models without understanding, logically, the core concepts (e.g., stereochemistry) they represent because models would not always be accessible in all situations. Dr. Petrosian’s recommendation is an astute one, especially given that students self-identified cost as being a potential factor deterring them from purchasing and using concrete modeling kits (Chapter 4). Additionally, if these models are integrated effectively with the text, they should ideally lessen the chances that students will come to view models as static, standalone entities, as can often, unfortunately, be the case (van Driel & Verloop, 2002).

Taken together, these findings demonstrate a potential misalignment between faculty’s personal beliefs about chemical visualizations and how they perceive models, in

particular, to be of use in educational settings. In this latter instance, there is also some concern that individual faculty hold conflicting views of the role of concrete models in promoting student learning and that these views may cloud how models come to be used in their teaching practice. To explore this claim in greater detail, a closer examination of faculty instruction within the Organic Chemistry classroom is warranted. This is where I turn next.

Examining faculty's use of models in the classroom. When used effectively, models can greatly enhance students' understanding of complex topics in chemistry and serve as a viable means to engage students in understanding and applying scientific knowledge (Gilbert, 2005; Prins et al., 2009; Stull, 2012; Wu et al., 2001). Faculty in this study largely reported finding value in these features of models, though their beliefs about the functional role of models in the classroom varied widely. In an effort to also focus more closely on faculty's use of models as they relate to the teaching and learning of 2D diagrams in Organic Chemistry, classroom observation video was collected and analyzed. This analysis revealed that faculty were using concrete manipulatives either in ways that did not appear to promote students' representational competence, or simply not at all (as was the case for Prof. Cooper).

For instance, Dr. Roberts constructed ball-and-stick models for use during his lessons to illustrate what a molecule, shown in two-dimensions on the chalkboard, would look like in three-dimensions (Figure 6).



Figure 6. Screenshots from classroom observation video of Dr. Roberts' lecture on 2D molecular representations and stereochemistry

Although intended to make this relationship more apparent to students, these models were often extremely difficult to see from the back of the classroom (particularly in the

larger lecture hall illustrated in the top panel). In addition, Dr. Roberts spent a large majority of his time (>70%) performing holistic rotations of the model that appeared more of a distraction than a connection to the material being covered in the lesson. When later questioned about his choice to use this type of concrete manipulative, Dr. Roberts stated that “these [the ball-and-stick models] were what students were or should be most familiar with” and that “students need to comprehend how to use a model to illustrate what a Dash-Wedge, Newman, and Fischer diagram looks like in three-dimensions.” Though these instructional goals are important, particularly in promoting students’ representational competence in the domain (Gilbert, 2005; Kozma & Russell, 1997), Dr. Roberts did not provide any in-class opportunities for students to construct or manipulate ball-and-stick models, at least in the episodes I observed. Admittedly, this could have been due to constraints imposed by the large lecture format of the lesson (Paulson, 1999). Regardless, because Dr. Roberts did not make the above objectives clear to the students either at the start of or during the lesson, it is uncertain whether or not they came to understand the relationship being demonstrated between the 2D diagrams and the model in the way he had intended them to.

Dr. Petrosian’s use of manipulatives was comparable in so much as that the primary purpose of modeling appeared to be to illustrate the three-dimensional nature of molecules. Unlike Dr. Roberts, however, Dr. Petrosian often superimposed the model on top of a 2D diagram after drawing the latter on the chalkboard (Figure 7). This practice, he reported, was designed to allow students to visually map the placement of substituents on the 2D diagram to their placement on the model and to “see” how the bonds projected

toward or away from the viewer – relationships or skills he felt students typically had great difficulty in determining or performing, respectively.

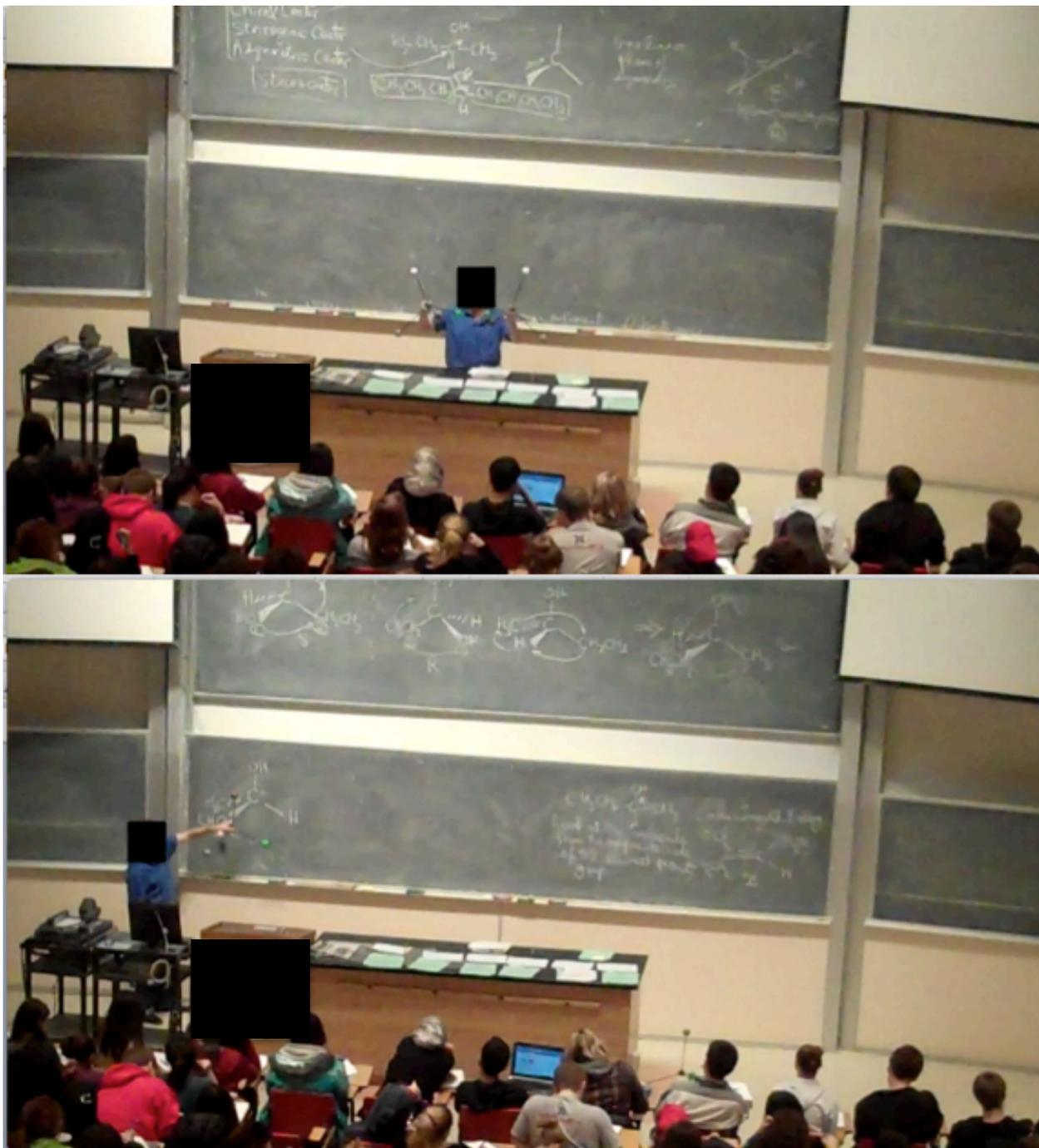


Figure 7. Screenshots from classroom observation video of Dr. Petrosian's lecture on 2D molecular representations and stereochemistry

Given Dr. Petrosian's use of lecture models, which are substantially larger than their ball-and-stick counterparts, this practice was likely rather effective. However, there is still a possibility that overlaying the model on the diagram may have instead made it more difficult for students to then see the diagram itself. If this were true, Dr. Petrosian's instructional move could potentially have resulted in greater confusion rather than reinforcing the development of students' representational skills in identifying salient relationships between the model and the diagram. Regardless, as was the case previously with Dr. Roberts, students were never afforded an opportunity to construct and test models on their own. Therefore, it seemed the students' responsibility to take a mental snapshot of Dr. Petrosian's models. This increases the cognitive demands placed upon students both in the context of the lesson itself, as well as when reviewing material in the future, when the lecture model is no longer available.

It is worthwhile to note also that the above data account for all instances in which faculty were observed making use of models in the classroom. Concrete models were never employed, for instance, to illustrate how one could translate between diagrams or to show the dynamic nature of molecules, though these were also central foci of the lesson. Rather, faculty relied upon algorithmic approaches when conveying these concepts to students. This included Dr. Roberts demonstrating a stepwise procedure for converting a staggered Newman projection into an eclipsed Newman projection prior to translating it into a Fischer diagram, which must be in an eclipsed conformation, as well as Prof. Cooper immediately drawing out various conformations of a Newman projection (Figure 8) without encouraging students to do so first.

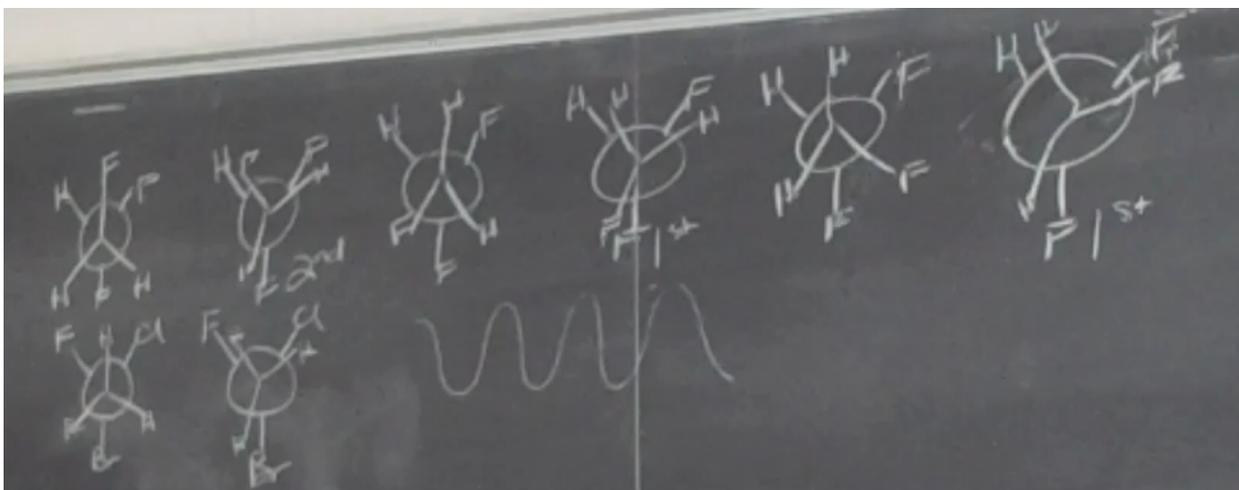


Figure 8. A screencapture of Prof. Cooper's depiction of various conformations of a Newman projection

While these approaches are not, practically-speaking, incorrect, and although they may have even led students to be successful in the short-term (e.g., in solving related questions on an exam), there is some fear that students may have only come to memorize what they had been shown without developing a deeper understanding of the topics at hand.

This fear is further compounded by the fact that these algorithmic techniques were not always accurately transmitted to students. During his discussion of how to translate from a Dash-Wedge diagram to a Fischer projection, for instance, Dr. Petrosian stated that it did not matter where students put substituents on the Fischer projection once the skeletal structure had been drawn. The segment below provides some context for this utterance.

Dr. Petrosian: Very quickly, in the time I have left, I need to go through the Fischer projection because it's very important, and you need to know it.

What you do in Fischer projections is... you have to number the molecule the way the name is [numbers carbons on his drawing]. Now you have to draw the Fischer like this [demonstrates]...don't draw anything until I'm done. You have to put the carbons on either the top or bottom of this vertical axis [because] this is the convention of the Fischer projection.

And then you have to realize what is attached to each carbon... - OH and -H in both cases. Where do we put these? It doesn't matter, so long as they are on the right [i.e., correct] carbon.

As Dr. Petrosian is speaking, students are rapidly copying down his drawing into their notebooks. The drawing itself is not accurate to begin with (he has drawn an enantiomer), and it seems clear that students have not attended to the actual verbal description/explanation provided by the instructor. Regardless, even if they had, the notion that substituents could be placed at random on the Fischer projection is flawed because this would not have preserved the spatial arrangement of substituents as depicted in the original Dash-Wedge diagram. When considered in light of empirical evidence suggesting that students struggle most with understanding the conventions of Fischer projections (Kumi & Dixon, in preparation; Stull et al., 2012), this instructional segment

is particularly troublesome and has the potential to impede students' development of representational competence in the domain.

Several macro-level (i.e., non-model specific) concerns were also identified from the interview and videodata that had the potential to influence students' development of representational skills. First, faculty collectively made very few attempts to discern whether or not students understood the material as the lecture progressed. Of the 250 minutes of classroom observation data collected, there was only one, two-minute segment in which a student asked a clarifying question to the instructor regarding how to translate from a Dash-Wedge diagram to a Fischer projection. In turn, the instructor simply provided the student with the correct answer, and the lecture proceeded. It is certainly possible that the student gathered enough information from this exchange to reach an understanding of the concept in question, but the chances of this information being assimilated into knowledge are questionable. Indeed, research has shown that while student questioning during lecture episodes is rare, this type of rapid-fire questioning technique does little more than promote superficial retention of facts (van Zee, Iwasyk, Kurose, Simpson, & Wild, 2001).

Second, in follow-up interviews, faculty (n = 2 of 3) admitted to assigning homework to students that, as Prof. Cooper put it, did not match the complexity of "what was being taught in class" or what "we [faculty] expected students to be able to do given the availability and accessibility of models." These assignments included requiring students to complete practice problems from the text and giving students teacher-generated problem sets to solve. Research suggests that textbook problems in particular often only require students to fill in substituents on skeletal structures of molecules, and

there is little emphasis placed on encouraging students to use alternative, non-algorithmic problem-solving strategies, such as modeling, to complete assigned tasks (Bodner & Herron, 2002; Kumi et al., 2013). In his comparative case study of a traditional versus active-learning based approach to teaching Organic Chemistry, Paulson (1999) states, additionally, that an overreliance on one type of problem or problem-solving strategy often leads students to perform poorly on other assessments, such as in-class exams, that may require them to apply or synthesize knowledge. Instead, cooperative activities, such as group responses to complex essay prompts or model-building exercises, ultimately lead to greater success and lower attrition rates among students in Organic Chemistry courses.

Lastly, interpretive analysis of interview data suggest that faculty in this study subscribe to specific pedagogical approaches that align with how they themselves were taught. Dr. Roberts' earlier statement in which he describes not having "fancy models" while he was a student and therefore not relying upon these visualizations, is one example. Alternatively, consider the following exchange between Dr. Petrosian and myself:

Researcher: How do you, kind of, try to align your teaching with the goals you have—how do you help students develop a deeper understanding of concepts related to molecular representations and models?

Dr. Petrosian: Well...you know, I guess I teach things the way I'd like to be taught. I mean, I want students to understand the concepts...but

[students] want a list of facts, and...[chemistry] sometimes seems like rote memorization and regurgitation.

Researcher: So you provide them with that list of facts?

Dr. Petrosian: I... well... sometimes.

Researcher: OK, what about using models?

Dr. Petrosian: As an undergraduate student...my teacher consistently used models for everything. He had a bunch of jerry-rigged models to show all kinds of things. So I like the idea of models, too, and thinks others and myself should try to use them [in class].

The examples of Drs. Roberts and Petrosian were juxtaposed intentionally. However, they illustrate an important point in that faculty's prior experiences as students can dramatically impact what pedagogical approaches they perceive to be most effective in the classroom, and not always for the better. Coppola and Jacobs (2001) argue that the challenge of adopting more constructivist methods of teaching, in this case a more models-based, hands-on approach to classroom instruction on molecular representations, is exacerbated by the fact that "science teaching leaves little room for doing anything but moving predigested information from textbooks to testing" (p. 4). Especially in large introductory courses, such as the Organic Chemistry classes discussed here, faculty then largely (and blindly) rely upon students' exam performance as an indicator of learning and modify instruction accordingly. Although necessary, there is, in reality, likely either little time for faculty to *deeply* reflect upon the teaching and learning occurring in their

classroom or a potential perception on the faculty's part that this is the case. I will return to the importance of reflective practice momentarily.

Interestingly, though, faculty office hours appeared to be one solution to this concern. Dr. Petrosian stated that:

Students show me the notes they took in lecture and tell me 'you drew this and gave an assignment of R or S to this molecule. I don't understand it.' And when they come in and I show them a model that I have in my office, and say 'look, this is the same molecule; this bond is coming toward you [extends arm outward] and this bond is going back [points other arm in opposite direction]' and they look at the model, they say 'ahh... I understand what you're talking about.' We work problems and questions together, and I have actually allowed them to take the model home with them to practice.

From this remark, it is evident that these office hours serve two functions. First, they relieve time constraints imposed by formal lecture meetings, allowing greater opportunities for faculty to engage in other methods of individual or small-group instruction, including the use of concrete models to support student learning. Research suggests that this preoccupation with time is not unusual. As a result of conducting semi-structured interviews with 39 Brazilian science teachers, Justi and Gilbert (2002b) showed, for instance, that chemistry faculty often struggled with balancing time requirements against content demands, leading them to favor more didactic modes of instruction.

Second, in contextual comparison to lecture settings, office hours provide a more personalized space in which student-faculty interaction can occur. Because students often view Organic Chemistry as a “killer course” (Grove & Lowery-Bretz, 2012), it is not surprising that they turn to office hours for supplemental instruction and support, and not without just cause. Greater student-faculty interaction can potentially lead to improvement in students’ critical thinking skills, course performance, and interest in science (Lancaster, Walden, Trytten, & Murphy, 2005). However, office hours are potentially only a Band-Aid. They do not ensure that student learning is taking place, nor are they accessible to all students. Instead, I argue, those same practices employed during office hours, if found to be effective, must then be transferred into the classroom. This is, nevertheless, a difficult feat to accomplish.

Beliefs about improving instruction: Adopting a reflective approach. When asked to describe what obstacles or extenuating factors might inhibit their ability to effectively teach students’ about 2D diagrams and the affordances concrete models provide for translating between these diagrams, I was surprised to find each participant report that there were none or, as Prof. Cooper stated, none that were “noteworthy.” Specifically, faculty stated that they did not feel limited either by their own degree of subject matter or pedagogical content knowledge, nor did they believe that there were constraints at the department or administrative levels (such as lack of professional learning communities or access to resources) that prevented them from performing their job. This perception may be resultant from the fact that two out of three of these faculty members has, in some capacity, spent more than a decade serving as an instructor for the

Organic Chemistry I course at Andrews University. Therefore, they have likely had several opportunities to adapt and refine their pedagogical practice in response to commonly observed student difficulties during particular lessons related to the above concepts, student feedback received via course evaluations, and feedback received from the university. However, it must be cautioned that this does *not* predicate that faculty have done the same extensive, finer-grain formative analysis of their teaching practice, for instance by iteratively collecting student feedback regarding their [faculty] use of 3D models in the classroom.

To explore this possibility further, I first wanted to ascertain to what degree external mediators might influence faculty's expressed views. I subsequently inquired, therefore, as to whether or not faculty believed participating in instructional workshops focused on modeling would serve to improve, or at least reinforce, their current use of manipulatives in the classroom, particularly as a means to promote students' understanding of 2D diagrams. My rationale for selecting this specific form of teacher professional development was two-fold. First, it is not uncommon for chemistry faculty at Andrews University to attend professional development workshops and conferences, including workshops in the field of chemistry education, and the department itself holds several seminars of this nature each semester. Second, previous research suggests that formal workshops often serve as a primary means through which chemistry faculty are introduced to better modeling practices in the classroom and are encouraged to adopt these practices as part of their own pedagogical repertoire (Molecular Visualization in Science Education Workshop, 2001). These workshops also ideally provide a suitable venue for faculty to exchange information regarding the effective use of models in

teaching, inciting participants to reframe their views on how these visualizations can be incorporated into the curricula.

Faculty taking part in the study collectively reported that, while informative, previous workshops that they had attended on this topic did not typically make a lasting, and influential, impression. Dr. Roberts stated, for instance, that he already felt comfortable teaching with concrete models and that while educational seminars introduced him to new ideas regarding the use of models in the classroom, they did not seem to show how one would “put these ideas into practice” or how “these ideas related specifically to [his] course.” This latter response is not unusual and is frequently cited in the literature as a chief complaint among teachers taking part in professional development experiences (Guskey, 2000; Stolk et al., 2009; Talanquer, Novodvorsky, Slater, & Tomanek, 2003).

Regardless, this sentiment is important for two reasons. First, it calls into question the accessibility and applicability of information presented to participants in these workshops. To a large extent, there has been a relative dearth of empirical findings on the effectiveness of faculty professional development for more than a quarter-century (Centra, 1978; Murray, 2002), and many professional development programs, including those at the K-12 level, are nothing more than “one-hit wonders.” In the foreword to Guskey’s (2000) *Evaluating Professional Development*, teacher and former executive director of the National Staff Development Council, Dennis Sparks, states that “to be successful, staff development must focus on the content that teachers teach and the methods they use to teach that content, and it must be sufficiently sustained and linked to daily classroom practice to affect student learning” (p. x). It is not surprising, therefore,

to find faculty reporting that there are limited lasting benefits of participating in these experiences if they do not align with their needs and subject area expertise.

Additionally, even in instances where faculty depart with new ideas for implementation in the classroom, this does not predicate that they will integrate them in a meaningful or effective manner. In their qualitative study of 87 experienced science teachers' knowledge of models and modeling, van Driel and Verloop (1999) found, for instance, that while most teachers held constructivist epistemologies regarding the uses of models as tools for teaching and learning, many of them still incorporated models into their practice in positivist ways. The evidence I presented in the preceding section corroborates this observation.

Secondly, and perhaps more critically, Dr. Robert's statement reflects a perceived dichotomization between chemists and chemistry educators or, to put it more broadly, practitioners and educational researchers/teachers. Some readers may find this distinction non-existent – chemists *are* chemistry educators, and vice versa. In the least, one cannot subsist without the other because they share a mutualistic relationship. However, research suggests that this perception is only recently gaining traction (Coppola & Jacobs, 2002). In their review on the place of the Scholarship of Teaching and Learning (SOTL) in the domain, Coppola and Jacobs (2002) argue that mainstream chemistry faculty (i.e., those with terminal degrees in chemistry) tend to marginalize the importance of conducting studies aimed at examining student learning, although their expertise in the discipline provides a necessary lens through which to consider how instructional reform can (and should) take place. The solution to this concern, the authors contend, lies in creating a welcoming space for chemistry instructors to investigate issues

relating to teaching and learning under the guidance of and with the collaboration of other chemists and science educators.

I cannot agree more wholeheartedly with this recommendation. While it requires that faculty have the time and resources necessary to conduct such investigations, they should be afforded the opportunity to do so, rather than having someone or something (e.g., a workshop) tell them how it should be done. In the context of the present study, these investigations could be something as simple as conducting a survey to determine if students own modeling kits and, if so, how frequently they use them and for what purpose(s). Alternatively, faculty could inquire as to why students do *not* make use of concrete models and then display for them pre-/post-test data from a modeling activity conducted in the classroom to illustrate the benefits these tools have for supporting student learning. Though these scenarios are hypothetical, they highlight several mechanisms by which faculty can gain immediate feedback on students' performance in and experiences related to the course, encourage students to adopt potentially advantageous strategies for improving their success in Organic Chemistry, and reflect on issues related to teaching and learning.

In lieu of attending workshops, this latter element of reflection, in particular, was identified by faculty as being highly important for determining how they refined their practice, including their choice of teaching strategies during the observed lecture on representations and stereochemistry. In their case study of the reflective practices of six exemplary mathematics professors, McAlpine and Weston (2000) describe reflective practice as a process that provides instructors with an opportunity to construct new knowledge about teaching, develop as professionals, and better understand how to

promote student learning. Furthermore, the authors state that reflective practice can occur prior to, during, and/or retrospective to instruction, suggesting that it is an iterative and continual process. The following excerpt from my interview with Dr. Petrosian is illustrative of this definition:

Researcher: So how do you go about improving your teaching, say of representations and stereochemistry, in future semesters?

Dr. Petrosian: The way I look at each semester is, first of all, look at the student evaluations.

Researcher: From previous semesters?

Dr. Petrosian: From the previous semester. That gives me some help as to what... of course, there are some students who write ridiculous comments, but the critical feedback helps me think about my teaching.

Dr. Petrosian: I also look at the performance on tests.

Dr. Petrosian: For example, if they're [students] on chapter 14 or 15 and still can't draw molecular diagrams or structures, it is then you decide 'look, I need to spend more time on basics and how to draw molecular structures and make sure they understand.'

Researcher: So...

Dr. Petrosian: And I've seen enough evaluations and tests to know what the common errors students make are. I'm upfront about telling future students what these errors are and how to avoid making them.

In the above dialogue, Dr. Petrosian demonstrates using reflective practices both concurrent with instructional episodes, as well as post-semester, and it is apparent in each instance that this process serves as a means by which he can contemplate and adapt his current teaching style. Furthermore, his last statement suggests that this process results in cumulative gains in both practical and pedagogical knowledge regarding how students learn and how to better promote learning in future semesters. It is important to note, here, that though the above statements are indicative of a *desire* to enact some type of instructional reform, they do not guarantee that such reform did or will eventually occur or that potential interventions were more efficacious in leading to student success. Evaluating the type(s) of change taking place in the classroom would require a longitudinal evaluation of Dr. Petrosian's lecture on representations and stereochemistry from semester-to-semester, an undertaking that might be a fruitful future endeavor.

Summary of Findings, Limitations, and Future Directions

A growing body of research suggests that providing students with access to concrete models may serve to enhance their representational competence in Organic Chemistry if they elect to use these models in meaningful ways, such as to solve visuospatial tasks in the domain (Bivall et al., 2011; Ealy, 2004; Stieff, Scopelitis, et al., in preparation; Stull et al., 2012). While it is clear, in part, that novices develop the skills required to achieve familiarity with the conventions and uses of models gradually over time, this process is expedited by the interactions students have with faculty in the discipline, particularly in classroom contexts. Using both classroom observation and interview protocols, this exploratory study sought to examine these interactions, focusing

on faculty's practical knowledge (van Driel & Verloop, 1999) regarding models and modeling in the Organic Chemistry classroom and in the field.

Consistent with my initial hypothesis, faculty were seen to generally hold positive views of models, both as explanatory and predictive tools in the field, and, at times to a lesser extent, as scaffolds for promoting learning in the chemistry classroom. One faculty member reported, for instance, that "models are essential to chemists because they provide us, faculty and students alike, a way to 'see' the chemical world in three-dimensions." In order to convey this relationship to students, faculty stated that they, and other teachers, should incorporate more models-based instruction into their pedagogical practice that provides students an opportunity to engage in constructing and using models both inside and outside the classroom. This included, for instance, greater use of modeling activities in recitation sessions, which are required of all Organic Chemistry I students at Andrews University, and providing students with easier access to models (for instance, by packaging them with textbooks), among other recommendations.

While this was the case, it was evident from analysis of classroom observation data that faculty's use of models in these contexts was largely misaligned with their broader desire to effectively incorporate more models-based practices into their courses. Models were often displayed in a format that was difficult for students to see, such as a ball-and-stick model being presented in the front of a large lecture hall, or they were used inconsistently throughout the duration of the lesson, such as utilizing a molecular model to illustrate a Dash-Wedge representation but not a Newman or Fischer diagram, nor how a model might be used to facilitate students' ability to translate between diagrams. Furthermore, students were rarely, if at all, prompted to ask clarifying questions or to

engage in the classroom “discussion” during these episodes. This undoubtedly resulted in the transmission of information from teacher to student, either successfully or unsuccessfully, with little assurance that the student could understand and make meaning of this information to construct new knowledge. Importantly, these practices were observed both for new and veteran faculty, suggesting that transparency between instructors’ beliefs about models and modeling and their actual use of them, pedagogically speaking, still remains a valid concern in today’s learning environments.

It is interesting to reassert, at this juncture, that some faculty believed the greatest amount of interfacing between students, instructors, and content (e.g., representations and models) occurred, potentially, during faculty’s office hours. Dr. Petrosian stated, for instance, that when students visit him in his office he works with them one-on-one using models and it makes concepts make sense. While producing promising results, this type of individualized instruction is not accessible to all students for any myriad number of reasons, nor is there any lasting evidence that students retain the knowledge gained from these experiences and interactions for a substantial duration of time. Rather, these observations reaffirm what has long been suspected –that teachers need to incorporate similar practices into the larger classroom environment in ways that allow students to construct their own knowledge and understanding of, in this case, chemical visualizations (Coll & Taylor, 2001). Furthermore, the fact that this is not largely already the case suggests that faculty may require guidance and support in doing so.

The above suggestion does not predicate, however, that accomplishing this goal will be an easy one, particularly given the limitations imposed by large class sizes and predominantly lecture-based instruction (Paulson, 1999). Research suggests that a viable

means to addressing this goal is to provide opportunities for faculty to attend workshops that allow for the dissemination of new ideas about the uses of visualizations in teaching (Molecular Visualization in Science Education Workshop, 2001). Interestingly, though, faculty in this study did not believe that these workshops or interventions would be beneficial because they would presumably be decontextualized from the ways in which models were being used specifically in their classrooms. Instead, all three of the faculty interviewed reported that better teaching practices, including the incorporation of models into one's instructional repertoire, were "learned on the job" by reflecting on student evaluations and feedback from previous semesters and putting those suggestions into action. Given the potential role of reflection in improving teaching and learning in the academy (McAlpine & Weston, 2000), attention to this detail is, if nothing else, a fundamental step in the right direction.

Regardless, there are several broader concerns to contend with. First, although faculty interviews were conducted post-observation, instructors were aware that I would be visiting their classroom on select days when representations and stereochemistry were being taught. This could have biased teachers into using models, even in ineffective ways, when they would not have normally done so.

Additionally, given the small number of faculty taking part in the study ($n = 3$) and the fact that the study was carried out over a single semester, it is not entirely clear how faculty's use of models and their teaching of molecular diagrams changes from semester to semester or how the views presented in this chapter reflect the community's broader views and practices regarding model use in the classroom. There are several possible solutions to this problem, including conducting a longitudinal study on faculty's

changing views of models and their uses in the Organic Chemistry classroom, comparing graduate teaching assistant's perceptions of and uses of models to those of full-time faculty, and examining how professional development opportunities for faculty might impact their views of models and modeling in the field, each of which is a profitable area for further exploration.

CHAPTER 7: COMPREHENSIVE SUMMARY AND IMPLICATIONS FOR TEACHING & LEARNING

Structural diagrams have become ubiquitous in chemistry, particularly organic chemistry, to the point where Ege (1989) contended that “Professional organic chemists cannot talk to each other without drawing structures” (p. 2). (Kozma et al., 2000)

Diagrams are part and parcel of chemical discourse. As such, developing the representational competence necessary to appropriate, manipulate, and make meaning of this form of visualization is essential for success in the domain (Gilbert, 2005; Kozma & Russell, 1997). While experts can perform these skills automatically, novices often cannot. In an effort to promote competency in this latter population, a growing body of research has suggested that educators should provide students with access to and opportunities with which to engage with concrete models or other manipulatives (e.g., virtual models), as these tools can render in three-dimensions what a diagram shows only in two (Stull et al., 2012; Wu & Shah, 2004). Given the heavily intangible and visuospatial nature of the discipline, this tactic is intended both to increase low-spatial students’ success in Organic Chemistry and to reinforce high-spatial students’ conceptual understanding of chemical phenomena by bringing the unseen world to life.

While this may be the case, it cannot be assumed that simply because students are provided with and even encouraged to use concrete models that they are capable of and/or prefer doing so. In their quasi-experimental analysis of 153 undergraduate Organic Chemistry students’ accuracy at translating between two, 2D diagrams with or

without the aid of concrete manipulatives, Stull and colleagues (2012) reported that it was only those students who *used* models in purposeful ways (e.g., aligning the model to match the target diagram) who showed significant gains in performance on the battery of translation tasks, although accuracy on these items was also found to be mediated, in part, by a participant's level of spatial ability. Furthermore, informal follow-up interviews with students revealed that a large majority of them elected not to use models because they found these tools confusing or too time-consuming to manipulate, or because they preferred more algorithmic problem-solving approaches.

Aside from their practical ramifications, these findings are important for two reasons. First, they beg a closer examination of how students are making use of concrete models under varying conditions – when they are pre-constructed, when presented as a modeling kit, etc. Second, they suggest that deeper analysis of and reflection regarding the reasons *why* students elect to make these choices is warranted.

In this dissertation, I argued that analysis of both cognitive and contextual factors leading to students' development of representational competence in the domain was an appropriate lens through which to explore these fundamental goals. I showed, importantly, that while model users (i.e., those who make use of models on >50% of trials) perform significantly better on representational translation tasks than non-users and while forced model use (as was the case for the 3D-only cohort in Chapter 4) appears also to increase one's success on the RTT assessment, students are reticent to construct models of their own when given the opportunity to do so and often suffer as a result. These actions and choices, I further demonstrated, are likely shaped largely by students' own perceptions of models and modeling, as well as the ways in which they observe

faculty making use of concrete models in the classroom. This chapter briefly revisits these major elements, namely: a) the role of concrete models; b) the role of students' perceptions of models and modeling; and c) the role of faculty's perceptions of models and their modeling practices in the classroom, and discusses their implication for teaching and learning. The chapter concludes by considering the potential application of these findings to other scientific disciplines.

Comprehensive Review of Results

What is the Role of Concrete Models?

The premise for the work presented in Chapter 4 was that model access and orientation (or mode of presentation) could have a significant impact on students' success at translating between a Dash-Wedge, Newman, and Fischer diagram of a given molecule. Specifically, my research built upon earlier findings from Stull and colleagues (2012) by comparing student performance on a series of representational translation tasks (RTTs) when students either: a) did not have access to concrete models; b) had access to pre-built models; c) were provided a modeling kit from which they could construct a model; or d) had access only to a 3D model and *not* an initial 2D diagram. Three important findings emerged from these studies.

First, the frequency with which students autonomously constructed models was relatively low (<40%). Given that this experimental condition most authentically represents how students would engage with models in traditional Organic Chemistry courses nationwide (Ingham & Gilbert, 1991; Small & Morton, 1983), it is important to consider why this is the case. In their semi-structured interview study of 39 Brazilian

science teachers' beliefs about modeling and the implications of these beliefs for the education of modelers, Justi and Gilbert (2002a) assert that "the construction of a model *de novo* involves perceiving the emergence of macro-level properties (those of the complete model) from those at the micro-level (those of the components of the model)" (p. 374). Given my observations regarding students' perceptions of models and their expressed reasons for either using or not using manipulatives, it is plausible that low model-building rates were attributable to students' inability to understand this relationship. Indeed, 9% of students in a subsequent study self-reported finding models confusing, and 39% stated that they were hesitant to use models because no instruction had been provided on how to build and/or use these tools (see Chapter 5). It is important to note also that much of this confusion may have been exacerbated by the fact that the ball-and-stick models employed in these studies reflect few properties of the actual molecules they represent (e.g., differences in size or bonding properties of atoms, types of bond lengths and angles) (Molecular Visualization in Science Education Workshop, 2001).

Despite this, all but one student in the model-building cohort could successfully construct a model when asked to do so, suggesting that individuals in this group likely *did* possess the representational competence necessary to understand how the parts formed the whole. I therefore believe it is much more likely that students' limited proclivity to build models is due simply to their perception that constructing models is too time-consuming a task and/or that algorithmic approaches to solving visuospatial problems, such as the items on the RTT, are just as accurate and more efficient than using concrete manipulatives for the same purpose. Survey and semi-structured interview data

corroborate this claim, and analysis of classroom observation data revealed a critical link for the emergence of this belief. Specifically, faculty did not provide any opportunities for students to build and test their own models in the classroom, nor did they necessarily use lecture models in effective ways themselves. They also routinely chose to adopt more heuristic-based instructional approaches in lieu of using models when introducing new topics (e.g., stereochemistry) and when demonstrating to students how to translate between representations.

A second key finding gained from this series of studies was that students receiving access only to 3D concrete models performed significantly better on the RTT than those who were initially shown only the 2D diagram. This discovery was both surprising and intriguing given that students collectively spend a larger amount of time interacting with diagrams than they do with models, at least in the context of Organic Chemistry courses at Andrews University, and the fact that students' exposure to diagrams in textbooks and other forms of scientific media is pervasive (Hegarty, Carpenter, & Just, 1991; Kumi et al., 2013). In addition, these results are counter to other current reports in the field, which have shown greater performance gains for students in 2D-only versus 3D-only experimental conditions (Oke & Alam, 2010). For instance, in their comparative study of the effectiveness of 2D and 3D visualizations in promoting students' understanding of the structure and nomenclature of organic molecules, Oke and Alam (2010) had 205 senior secondary students take part in an intervention in which they were randomly assigned to view a CD-ROM illustrating either 2D skeletal formulae and animations of alkenes, alkynes, and their derivatives or 3D renderings of these molecules. Using a pre-/post-test study design, the authors showed that students in the 2D condition

were then better able to answer questions about these molecules than their 3D counterparts. This finding was attributed to the fact that students were more familiar with the 2D visualizations based on their previous classroom experiences, and therefore scored higher on the assessment than their peers in the 3D condition who may have been less familiar with those (3D) forms of visualization.

Certainly, a permutation of this same argument could be used to explain the results from my own study. As an aggregate, students might have been equally as familiar with the concrete models as they were with the 2D diagrams displayed in the RTT, and, because models have the potential to support students' ability to translate between chemical representations, those students in the 3D-only cohort outperformed the 2D-only participants. However, I am not certain that this entirely captures what is happening. Instead, there is some credence to the notion that because students are, in essence, required to use (or at least view) models in the 3D-only condition and because accompanying 2D diagrams are removed from the tasks that this may actually reduce the cognitive demands placed upon participants in this treatment group. This may be especially true given research suggesting that students' success at completing visuospatial tasks in the domain decreases as their need to coordinate multiple representations increases, even if these representations are all familiar in nature (Kozma, 2003; Kozma & Russell, 1997, 2005; Stull et al., 2012).

Conversely, it could have also simply been the case that instructors were placing greater emphasis on modeling during the semester in which this study was conducted as compared to previous semesters. If this were the case, then these results indicate that faculty should place greater emphasis on articulating the positive and negative values of

models and modeling in the context of chemistry. This, in turn, may lead students to develop a better understanding of the role these models have in the discipline, both for the purpose of scientific research, as well as for the purposes of reasoning and problem-solving.

Lastly, this series of studies reaffirm that students' level of spatial ability and the modeling behaviors they engage in are predictive of their success on visuospatial tasks in the discipline, such as the RTT. Specifically, students with higher spatial aptitude were found to complete more translation tasks accurately than their low-spatial peers – a finding that has been shown repeatedly throughout the literature (Coleman & Gotch, 1998; Harle & Towns, 2011; Pribyl & Bodner, 1987; Stieff et al., 2012). Importantly, however, both high- *and* low-spatial students were observed to make relatively equal use of concrete manipulatives across each of the individual studies. For those students who used these models in meaningful ways, such as fully aligning (Match-Align) the model to match the desired target representation, regression analyses showed that there was a greater likelihood of improved achievement on the RTT, including greater achievement, specifically, on challenging items (e.g., greater accuracy at translating to or from a Fischer projection for students in the 3D-only modeling condition).

While this was the case, a large percentage of participants, including those receiving access to pre-built models, chose not to use manipulatives on the RTT. I have already reviewed potential reasons for why this may be the case above, but I want to take a moment to reinforce the fact that discerning the relationship between a given model and its 2D referent is no easy feat. Some students may not be aware of the benefits of having access to a 3D model, even though these benefits (e.g., being able to physically rotate the

model) seem, to the trained eye, extremely transparent (Bucat & Mocerino, 2009). Likewise, it is speculative, though supported in part by the literature (Stieff et al., 2012; Stull et al., 2012), that the novices taking part in my research are attempting to access chemistry content knowledge, perform spatial and relational reasoning, and evaluate potential correct responses all simultaneously and in their minds in an effort to solve items on the RTT. Given that the cognitive demands imposed by the combination of these processes alone is likely overwhelming to novices, it would come as no surprise to find that students would therefore see models as an impossible, additional complexity to attempt to accommodate.

Regardless, in light of all of this evidence, the remaining question, then, is: What does all of it mean? From a theoretical stance, the preceding studies on students' use of concrete models to translate between common 2D diagrams in the field of Organic Chemistry reveal that the majority of students possess the representational competence necessary to recognize the conventions of concrete models (specifically, ball-and-stick models) and are capable, when asked, of constructing models of their own. However, their ability to accomplish and/or apply these skills is limited by one of two factors, namely: a lack of understanding of the conventions of the 2D diagrams themselves (particularly Fischer projections) or a lack of practical knowledge regarding how to use models as problem-solving tools.

To address the former concern, faculty might consider restructuring the way(s) in which they teach molecular representations in the classroom. This would include not only more focused instruction on Dash-Wedge, Newman, and Fischer diagrams, but also ample opportunities for students to engage in in-class modeling activities (perhaps in

recitation) that make the conventions of these diagrams more explicit, to ask questions and to work collaboratively with faculty and peers, and to practice translating between these representations on both formative and summative assessments of learning. Even if students still elect *not* to make use of concrete models subsequently, this practice should still lead to an increased chance that students, both low- and high-spatial, will succeed in their study of Organic Chemistry.

Resolving the latter issue, in comparison, appears to require more than just teaching students how to effectively and efficiently use concrete models, though this is certainly necessary. It requires a fundamental reshaping of the way students perceive and value models and modeling in chemistry. The two, though, appear inextricably linked. The role of visualizations in the social construction of scientific knowledge is well-documented (Kozma, 2000), and there is no reason why these same social modeling practices and discussions about the value of models in the scientific world cannot be transferred into the classroom in effort to promote students' representational competence in the domain.

What is the Role of Spatial Ability?

Although the use of 3D, physical models can indeed support students' development of representational competence, there are also a multitude of instances across scientific domains in which recreation of the three-dimensional world necessitates the use and interpretation of 2D diagrams alone, thereby placing increased cognitive demands on an individual's spatial ability. Research examining biology and medical students' success at drawing anatomical cross-sections, a task found to be especially

challenging for low-spatial students, is but one example (Hegarty et al., 2007; Rochford, 1985). Perhaps not surprisingly, outcomes derived from analysis of novices' interactions with 2D diagrams and 3D manipulatives in Organic Chemistry, a spatially complex domain itself, have generally revealed few exceptions to this trend (Harle & Towns, 2011).

While this is the case, I did not want to assume a zero-order correlation between spatial ability and student performance on visuospatial tasks in my own research. Therefore, studies one and two of this dissertation focused, in part, on the potential relationship between novices' spatial ability and their accuracy on the RTT assessment developed by Stull and colleagues (2012). In both cases, spatial ability was found to be a moderate, positive predictor of overall success ($r = 0.471$ in study one, and $r = 0.460$ in study two). These results are in agreement with previous reports in the field (Hegarty et al., 2009; Pribyl & Bodner, 1987; Stull et al., 2012).

More importantly, however, the data in these studies collectively indicate that individuals with low and high spatial ability made relatively equal use of concrete manipulatives across the modeling treatment conditions. In fact, in certain instances, such as in the case of the 3D-only cohort, there was no statistically significant difference found between low- and high-spatial students' average performance on the RTT. These results are promising, and add to a growing body of literature suggesting that the effective use of models by novices may not only help reduce the challenges low-spatial learners face in heavily spatial domains such as Organic Chemistry, but also augment high-spatial students' performance on visuospatial tasks in the discipline as well (Stull et al., 2012).

What is the Role of Students' Perceptions of Models and Modeling?

In addition to examining *how* interaction with concrete manipulatives impacts students' development of representational competence in Organic Chemistry, it is equally critical to understand what views students themselves possess of models and modeling in the domain. Using survey and semi-structured interview protocols, previous studies in the field have shown that a large proportion of secondary science students hold naïve realist epistemologies of models in which these visualizations are seen as being exact or near-exact replicas of the phenomena they intend to represent (Grosslight et al., 1991; Treagust et al., 2002). Despite this, several students across these studies were aware both that models could be used for predictive and explanatory purposes and that the ways in which scientists make use of models could change as a result of emergent evidence or theories in the field – views commonly held by expert chemists. When taken together, the authors argued, these findings suggest that students need “more experience using models as intellectual tools, more experience with models that provide contrasting conceptual views of phenomena, and more discussions of the role of models in the service of scientific inquiry” (Grosslight et al., 1991, p 799).

Building upon this earlier work and the findings presented in Chapter 4, I conducted an exploratory, mixed methods study of Organic Chemistry I students' perceptions of models (including representations) and modeling in the discipline. Results indicated that more than half of participants in my sample ($n = 187$) either agreed or were not sure if models should be an exact replica, while 67% agreed that they at least needed to be close to the real thing. Interestingly, students whose perceptions most closely aligned with a realist epistemology of models often identified the features of everyday

scale models, such as K'NEX®, as being analogous to what a chemical model should resemble. For instance, these participants (n = 18) stated that, just as the instructions contained with the toy model prompted the builder to construct *exactly* what was shown in the “blueprint,” so too was there a correct way to construct a model –in this case, a ball-and-stick model.

While concrete models in chemistry *do* need to be exact in many ways (e.g., preserving the spatial arrangement of substituents as they would actually be found on the molecule), there is some concern that students will come to see these visualizations, and the entities they represent, as being static if the degree of precision becomes overexaggerated and the dynamic nature of these models is not emphasized. In some sense, the fact that students retain such naïve realist views is not surprising because when we (educators) require students to construct models of their own, we *do* often judge them as being accurate or inaccurate – you either built a model of the molecule I asked you to represent or you did not. We also, as students’ self-reported, do not always provide sufficient opportunities for them to build, test, and interact with models in classroom settings. We must therefore not only be open and willing to contend with student difficulties and misconceptions if our long-term goal is to promote representational competence in this population, but also be cognizant of the practical limitations we (unknowingly) impose upon students and the ramifications of these actions with regard to their preferences to either make use of manipulatives or not.

Despite the commonality of this perception, though, an overwhelming percentage of participants (>85%) still agreed that many different types of models existed to explain chemical phenomena and believed that these models possessed multiple uses throughout

the field. One student noted, for instance, that both 2D and 3D renderings of a Newman projection were needed because, collectively, they provided [her] with key information regarding the stability of the molecule and allowed her to physically see how to reduce steric interaction. Though unique to this study, beliefs of this nature are similar to those held by participants in Treagust and colleagues' (2002) study. This suggests, perhaps, that it might be of continued benefit to all students in Organic Chemistry courses at Andrews University to also have broader exposure to the role of modeling in chemistry, as well as in other scientific disciplines. One means of accomplishing this goal might be to increase the use of models in lecture, recitation, and laboratory contexts or to have experts discuss how they make use of models in their own professional work (Kozma, 2000), as this would highlight for students the practical and real-world applicability of these visualizations.

In considering the novel contributions of my own research to the broader chemistry education community, it is necessary to discuss two important findings that emerged. First, while students generally agreed that graphs, animations, diagrams, and concrete and virtual manipulatives could all be considered models, less than 50% believed that a model could be a chemical equation or reaction mechanism. When asked to describe why they held this belief, students most frequently described equations as being "examples" or "illustrations" rather than as being malleable or as serving an explanatory purpose, as they felt models should. This finding is fascinating not only because it aligns well with students' perceptions of the purposes and uses of models in chemistry (see above, as well as Table 10), but also likely reflects the fact that students possess greater familiarity with scale (e.g., ball-and-stick models) rather than symbolic

forms of modeling (Chamizo, 2011; Laszlo, 2011), at least in the context of this study, and are therefore using the characteristics of these scale models as a basis for evaluating whether other visualizations in the field can also be classified as models.

Although the research presented in this dissertation is most principally concerned with students' use of concrete models and the role these models have in supporting novices' ability to translate between 2D diagrams, achieving true representational competence in the domain is contingent upon understanding and identifying the relationship between multiple forms of chemical visualization (Kozma & Russell, 1997) – reaction mechanisms and equations included. This is especially true given that students are, at least occasionally, encouraged to use concrete models to predict or represent the products of chemical reactions in Organic Chemistry courses at Andrews University (Olimpo & Dixon, 2013). If nothing else, these data identify a core set of features that students self-report as being either beneficial or negative aspects of models and modeling in Organic Chemistry. As a result, this information provides faculty whose goal it is to promote students' representational competence in the domain with suitable insight regarding how to go about doing so.

A second, important finding pertains to students' beliefs about how experts in the field make use of models. I was surprised to find from analysis of survey data that more than 60% of students agreed that existent models were too simplistic to describe the phenomena experts were interested in studying and/or that experts did not need to make use of models because they already possessed sufficient content knowledge to solve novel questions or problems in the domain. Follow-up interviews suggested that this perception might be linked to the fact that students see what experts do as being abstract

– too abstract, in fact, to be represented by a model unless said model is complex and, as some students self-reported, virtual in nature. Likewise, a significant number of students (n = 12) did not seem aware of the various types of models created by experts and the specific purposes of these models, perhaps because they lack an understanding of the historical significance of these visualizations to the chemistry community or because when experts' use of models *is* discussed, it is done so in a factual, transmissionist way. These issues need be addressed as part of the curriculum.

It is also possible that this observation may be due to the fact that students are conflating the term “expert” with “teacher.” Research suggests that students commonly view instructors as being omnipotent (Britzman, 1986), and since the faculty at Andrews University make use of models in discrepant ways (see Chapter 6), it may appear to students that “experts” do not need such tools, especially when they have other affordances and resources, such as textbooks, widely available to them. This mindset is likely reinforced by the fact that students self-reported having limited instruction on how to construct and use models and little or no opportunities to engage in modeling practices in the classroom – all elements under the primary control of the teacher. Because it is unclear, in this case, whether addressing these issues would predicate an expansion of students' views of models and modeling as well as their representational competence in the domain, I propose that future studies might seek to establish empirical evidence comparing a traditional chemistry classroom to one in which the above concerns are accounted for.

Looking Ahead: How Faculty use Models and What this Means for Instruction

Faculty perceptions and uses of models. Several studies have examined students' use of manipulatives and the role of these visualizations in supporting the development of students' representational competence in chemistry (Hinze et al., unpublished; Kozma & Russell, 1997; Stull et al., 2012; Wu et al., 2001; Wu & Shah, 2004). However, none, to the best of my knowledge, have concurrently explored how teachers make use of models in the classroom and/or the perceptions these instructors have of models and modeling in their discipline, though substantial research has been conducted in this latter area (Harrison, 2001; Justi & Gilbert, 2001, 2002a; van Driel & Verloop, 1999, 2002). Adopting a mixed methods approach, the objective of my study was to address this need, particularly by characterizing university faculty's perceptions of and uses of models in the Organic Chemistry classroom.

Conducting semi-structured interviews with faculty revealed that these individuals typically held sophisticated epistemologies of models – ones in which models were seen as useful for predicting or explaining chemical phenomena and for co-constructing or communicating scientific knowledge. These findings align well with previous reports in the field (Gilbert, 2005; van Driel & Verloop, 2002) and are thus unsurprising. van Driel and Verloop state, for instance, that “several categorizations or typologies of scientific models have been described...models may be characterized as descriptive, explanatory, or predictive...in any case, models play an important role in the *communication* between scientists” [emphasis their own] (pp. 1256-57).

Interestingly, however, when questioned about the applications of models and modeling in the *classroom*, faculty's perceptions of these visualizations varied

dramatically and, in most cases, were contradictory to their earlier reported beliefs. Some faculty felt, for instance, that models were not a necessity if “good instruction” was already taking place in the classroom. Others believed that models would be too confusing for students, many of whom already struggled with understanding the conventions of the diagrams or molecules the models intended to re-create in three-dimensions. Analysis of classroom observation videodata reaffirmed these beliefs, as faculty ($n = 3$) were seen either not making use of models during instructional episodes related to the teaching of stereochemistry and molecular representations or using manipulatives in ways that appeared un conducive to student learning. This included using ball-and-stick models in lieu of lecture models and failing to use models to illustrate the steps necessary for translation between representations, among other practices.

Furthermore, faculty admitted assigning students homework that was not at the same complexity as what they expected students to be able to achieve on exams or other summative assessments. A review of several common Organic Chemistry textbooks used by our university’s peer institutions revealed that many practice problem sets, which were frequently used by instructors in my sample, simply require students to place substituents onto pre-existing skeletal structures of molecules with little or no acknowledgement of preserving the spatial arrangement of substituents and little emphasis on the steps necessary to accurately translate between representations (Kumi et al., 2013). In other words, we found these types of tasks do little to promote students’ representational competence in the domain.

Despite these findings, though, some faculty still acknowledged that models could have a potentially beneficial role in promoting student learning or, at least, in increasing students' exposure to this type of visualization. Dr. Petrosian suggested, for instance, that publishers might go so far as to package modeling kits with textbooks in an effort to increase the likelihood that students would make use of these manipulatives. This certainly does not predicate that students will come to *effectively* use these tools; however, his recommendation is a step in the right direction.

When questioned about other potential barriers and motivators for adopting models-based practices in the classroom, I discovered that faculty appeared to make the majority of their decisions regarding instructional reform based on previous student evaluations and summative data collected throughout the semester. Faculty reported that they were less likely to acquire and implement new modeling approaches in the classroom as a result of attending chemistry education workshops and seminars, which they often found either to be “one hit wonders” impertinent to their own interests or teaching context or lacking guidance in how one should put workshop ideas into action. Though such workshops are a favored mode of disseminating new information (Molecular Visualization in Science Education Workshop, 2001), this data suggests that alternate forms of professional development might also be necessary.

This concern is echoed throughout the K-16 professional development (PD) literature. In a recent review of current research on the status of PD for elementary and secondary teachers in the United States and abroad, Darling-Hammond and colleagues (2009) reported that student learning gains and success in the classroom were significantly associated with teachers who participated in intensive, sustained

professional development opportunities that were connected to the teacher's practice, rather than the "occasional, one-shot workshops that many school systems tend to provide, [and] which generations of teachers have derided" (p. 9). Importantly, however, the authors acknowledge that these types of experiences (i.e., positive, sustained professional development) are routinely lacking and teachers often do not have access to professional development that addresses most, if not all, of these criteria.

In academia, issues related to faculty PD are exacerbated by the fact that, as Sunal and colleagues (2001) describe it, "science faculty members have little, if any, professional training in teaching at the college level" (p. 247). In their study regarding barriers to change in post-secondary education, the authors found that science faculty's perceived realities of the classroom often prevented or limited the effectiveness of planned reform. Among other things, this included faculty reporting that lecturing was the only appropriate instructional method when teaching to a class of 250+ students and that there were few, if any, rewards at the departmental or institutional level for demonstrating teaching excellence or innovate pedagogy.

Implications for instruction and professional development. Taken together with previously reported findings in this dissertation, it is clear that, pedagogically speaking, much can be done to better develop students' representational competency in the domain. I propose a three-pronged approach to meet this need that includes, namely, a focus on better faculty preparation and professional development, more explicit instructional goals and practices, and better assessment of student learning as it pertains

directly to their understanding of and ability to translate between Dash-Wedge, Newman, and Fischer molecular diagrams. I discuss each of these components briefly below.

Preparing faculty for using models in the classroom. It is evident, at least in this context, that some faculty are already making use of concrete models as part of their teaching repertoire, albeit in potentially ineffective ways. Planned professional development should therefore focus on helping instructors to improve their practice and, even more importantly, I would argue, incorporate more opportunities for their students to engage in modeling exercises in the classroom. Studies suggest that this must be done cautiously, however, as faculty may be reticent to reconsider their current instructional approach(es), especially given their responsibilities as either teaching or research faculty (or both) in the department (Sunal et al., 2001). In addition, such opportunities should not alienate faculty but instead adopt a teacher-supportive, student-centered stance. This might include inquiring as to how faculty are currently making use of manipulatives in their teaching (much like was done through classroom observation here), as well as working with faculty to identify specific instructional objectives that could better be accomplished through the use of models (e.g., illustrating to students how to translate between diagrams), among other features. Regular milestones should likewise be established, at the instructors' discretion, to ensure that any issues emergent from curricular intervention or reform are addressed in a timely manner.

A second important and necessary issue to contend with is the fact that providing professional development opportunities for current educators does not serve to prepare *future* faculty. At large institutions especially, graduate teaching assistants (GTAs) often

have a significant role in the instruction of undergraduates (Marbach-Ad et al., 2012), and, since at least a fraction of them will likely go on to join the professoriate, it seems plausible that this would be an ideal population to target. Current research suggests that preparatory programs for GTAs have generally been lacking both in duration and in quality and have focused almost exclusively on non-domain-specific pedagogical concerns, such as teaching methods, learning styles, and instructional design (Roehrig, Luft, Kurdziel, & Turner, 2003; Talanquer et al., 2003). In their study of the experiences of first-year laboratory GTAs, Roehrig and colleagues (2003) used semi-structured interview data to show, for instance, that many graduate teaching assistants are ill-prepared to enact inquiry-based practices in the chemistry classroom, though these practices are favored, because they lacked role models or insight on how to implement these active learning-based strategies. The authors conclude by suggesting that GTAs should spend time reflecting on their own teaching, perhaps by viewing a videotape of one of their lab sessions, as well as observe experienced GTAs to gain a sense of the student-engagement and questioning techniques expected of them. Though conducted in a laboratory setting, these same recommendations, at least in some aspects, would be suitable and appropriate for lecture and/or recitation settings.

These suggestions also raise a much broader question, then, regarding what professional preparation experiences for GTAs and future chemistry teachers should look like. While I agree with Roehrig and scholars' (2003) recommendations, I find Talanquer and colleagues' (2003) description of their College of Science's preparation program to more explicitly address how to prepare faculty to be "representationally

aware” in the chemistry classroom, a feature which is both pertinent and critical to my own research. These authors state that:

The program’s focus on science teaching also creates multiple opportunities to develop the prospective teacher’s pedagogical content knowledge...Through the different science education courses, and in the chemistry-teaching methods class in particular, students...reflect on the various levels of representation commonly used in the chemistry classroom: macroscopic, microscopic, and symbolic. Students also analyze the role of modeling and language in learning chemistry, discuss the strengths and weaknesses of analogical thinking, and learn how to foster intellectual skills for problem solving. (p. 1170)

In addition to enhancing participants’ subject matter and pedagogical content knowledge, it is clear that not only do participants in this program have myriad opportunities for interacting with peers university-wide, but that a well-structured, long-term program of this nature has the potential to draw high-quality students into the field of chemistry education. While this may be the case, this type of program, which was designed primarily for prospective secondary science teachers, would require a much greater investment in terms of time and resources on both the part of the GTA or faculty member as well as the professional development organizers. This is not to say, though, that a modified version retaining the same core principles could not be realistically adapted to prepare post-secondary educators.

Regardless, the above recommendations are just that: suggestions rather than guaranteed solutions. It is essential to note that while I *am* advocating for the use of models in the classroom, I am *not* arguing that a models-based approach is suitable for all faculty. Indeed, transmissionist modes of teaching would likely excel over modeling-based approaches if these models were used poorly or in non-constructivist ways. Rather, I am simply asserting that well thought-out, sustained, teacher-supportive professional development will not only hopefully allow faculty more time to reflect on and manage their own practice, but also afford faculty the chance to discover effective ways for improving student learning and representational competency in chemistry.

Practice problems are NOT the answer: A holistic recommendation for instructional reform. One seemingly straightforward but unsafe assumption is that increasing students' representational competence in the domain, including their ability to translate between 2D diagrams with and without the use of concrete models, is achievable simply by providing them with additional practice problems that are deemed to evaluate and enhance these skills. I have shown already that this is not the case, particularly because such problems typically require students only to recognize the superficial features of chemical visualizations without attending to their deeper structural elements (e.g., stereochemical properties) (Kumi et al., 2013). Research likewise suggests that students tend to be successful at solving these types of problems, no matter their complexity, only if they are explicitly taught general effective strategies for doing so, and that there is an overall lack of transfer of problem-solving skills to novel contexts (Chamizo, 2011; Gilbert, 2006). Gilbert (2006) states, for instance, that “students can

solve problems presented to them in ways that closely mirror the ways in which they were taught. They signally fail to solve problems using the same concepts when presented in different ways” (p. 958).

There are two important points to glean from this statement. First, it is clear that the quality and substance of instruction must align with intended course goals so as to support the development of students’ representational *skills*. With specific regard to students’ use of concrete manipulatives, for instance, it might be more effective to have modeling activities incorporated into multiple instructional units, rather than just a few, as this would provide students with additional opportunities both to engage in the practice of modeling and to witness the value models have for understanding multiple aspects of chemistry. Furthermore, if instructors make an effort to clearly illustrate the relationships between these models and other forms of chemical visualization in the process, as the literature recommends (Gilbert, 2005; Kozma, 2003; Stieff, Hegarty, & Deslongchamps, 2011), this should serve to increase both low- and high-spatial students’ representational competency in the domain.

It must be acknowledged, however, that concrete manipulatives may not be suitable problem-solving tools for all individuals and thus should not be forced upon students without at least considering the consequences of doing so. My own data, as well as that of previous researchers (Stull et al. 2012, as example), have shown that several students prefer more algorithmic approaches in lieu of modeling or are unsure how to integrate models into their existent repertoire of problem-solving strategies because they have not been provided instruction or guidance on how to do so. This, in itself, is not a cause for concern (or, in the latter case, an issue that could not be remedied). In fact,

because models are not always available for use, students should not come to rely upon these affordances. Rather, models should be incorporated into instruction to support student learning in ways that allow such learning to be *sustained* even when models are removed from the educational context.

This leads nicely to the second point. Instead of conditioning students to be able to solve one particular type of problem using one particular strategy, we, as educators, need to adopt a multifaceted pedagogical approach and provide students with greater opportunities to *apply*, *evaluate*, and *synthesize* new knowledge in ways that serve to enhance their representational competence in the discipline. This might be done by introducing more case studies or primary literature into the curricula that make use of novel 2D representations and engaging students in a discussion of the relationship between these representations, having students use cutting-edge visualization software or concrete models to explore issues relevant to today's society (e.g., modeling stereoisomers of chemical compounds and relating them to drug development), and/or by requiring students to give poster presentations of findings from the laboratory that demand the integration of multiple forms of representation, such as chemical equations, quasi-3D models, and diagrams. Through these means, students will not only receive greater exposure to the use of visualizations in scientific discourse, but also a foundational understanding of the important role these visualizations have for the scientific community.

Formative methods for assessing students' representational competence. The focus of this dissertation is not on the evaluation or development of assessments designed

to measure students' representational competency in chemistry. Regardless, this agenda is an important one, and assessment is both a necessary antecedent to and product of instruction. Research shows that summative assessments have long served as the primary measure of student achievement in chemistry and in other domains (Harlen & Crick, 2002), reportedly because they hold both students and educators accountable for establishing and achieving set learning standards and, due to the potential rewards and penalties associated with assessment results, raise the work ethic of both parties. However, especially when used alone, summative assessments often appear to do little more than inform us about students' short-term ability to regurgitate information. We then place these evaluations aside and proceed to the next unit (Harlen & Crick, 2002). At that point, we are too late, and the assessment has done little to inform us about *how* we could have or should improve student learning.

Like many others in recent years (Beatty & Gerace, 2009; Bell & Cowie, 2001; Treagust, 2012), I argue that more formative means of assessment are necessary in order to truly gauge student progress and success. Such assessments could take many forms and serve many functions. Following the context of this dissertation, these assessments might be used, for instance, to gather periodic feedback on students' understanding of chemical representations, the use of manipulatives to translate between representations, and their competency at using models. They might be a one-minute paper asking students to illustrate and describe the differences between conformers, enantiomers, and diastereomers of a molecule or a survey regarding a new modeling activity that was introduced. This is not to say that the design and evaluation of these assessments requires any less thought or attention than their summative counterparts. Indeed, formative

assessments can be just as constructive or inhibitory to learning depending on how they are delivered (Yorke, 2003).

However, when rigorous, this form of evaluation thrives from its ability to generate almost instantaneous feedback for students and faculty, providing declarative evidence for “what works” and what does not, pedagogically-speaking. Boston (2002), in her piece on defining formative assessment, captures this sentiment best when she states that:

...formative assessment helps learners become aware of any gaps that exist between their desired goal and their current knowledge, understanding, or skill and guides them through actions necessary to obtain the goal. The most helpful type of feedback...encourages students to focus their attention thoughtfully on the task rather than on simply getting the right answer. Formative assessment helps support the expectation that all children can learn to high levels and counteracts the cycle in which students attribute poor performance to lack of ability and therefore become discouraged and unwilling to invest in further learning. (pp. 1-2)

This latter statement is especially powerful given that a large number of students struggle with understanding concepts in Organic Chemistry and therefore perceive it to be a “killer course” (Grove & Lowery-Bretz, 2012). Creating contexts in which students can create and re-create knowledge, learn from their errors and triumphs, and engage with the curricula in formative ways is essential for challenging this stereotype.

Chemistry is, and will continue to be, a representation-rich domain. It is no trivial fact, therefore, that novices must come to be representationally competent should they wish to be successful in the field. The above discussion is meant to illustrate one manner by which to accomplish this task, stressing the need for a well-rounded approach that places equal attention on teacher preparation, instruction, and assessment practices.

Applications for other Scientific Disciplines

The use of concrete models and other forms of representation are not unique to the field of chemistry. Whether designed to depict micro- or macroscopic phenomena, these visualizations have been critical for the communication of such scientific knowledge as Watson and Crick's (1953) discovery of the DNA double-helix and Bohr's (1913) model of the atom, among other accomplishments, and are used throughout scientific texts and classrooms worldwide (Dimopoulos, Koulaidis, & Sklaveniti, 2003; Gilbert, 2005). It is not surprising, therefore, that this ubiquity presents a challenge for novices in the fields of biology and physics as well.

To remediate this concern, educational researchers in these areas have likewise called for the use of manipulatives to support students' conceptual understanding of complex topics and to enhance their representational competence in the respective domain. In one quantitative study examining the use of concrete manipulatives to improve student learning in the field of neurophysiology, Krontiris-Litowitz (2003) showed, for instance, that neurobiology students who engaged in constructing models of ion channels, nerve cells, and passive membrane properties (e.g., membrane permeability) of cells ($n = 12$) performed significantly better on a quiz containing

questions on these topics than a control who had not worked with manipulatives ($n = 10$). A follow-up study, in which student gains on a pre-/post-intervention assessment were measured, revealed that students in the manipulative group achieved the greatest grade improvement. These results, Krontiris-Litowitz argued, illustrate not only that concrete models can effectively enhance learning, at least in the context described, but also “encourage students to challenge their understanding of a topic” (p. 118).

Similarly, Zacharia and Olympiou (2011) analyzed 182 undergraduate physics students’ conceptions of heat and temperature before, during, and immediately following an instructional intervention in which students were randomly assigned to one of three experimental conditions: a) Physical Manipulative Experimentation (PME); b) Virtual Manipulative Experimentation (VME); or c) PME-VME combined sequence. Physical manipulatives included instruments (e.g., thermometers), objects (e.g., heaters and Styrofoam cups), and various other materials such as wood and water; these materials were re-created in the virtual environment. In all conditions, students were asked to complete the first four experiments in the Heat & Temperature (H&T) unit of the Physics by Inquiry curriculum (McDermott and The Physics Education Group, 1996). Using the H&T as a measure of conceptual understanding, the authors then showed that students in the modeling conditions, regardless of which one, held significantly more acceptable scientific conceptions of heat and temperature than did a control group ($n = 52$) who completed the experiments without the aid of manipulatives. As a result of their work, Zacharia and Olympiou therefore contended that both physical and virtual models could equally support student learning in this area.

The results I present in my dissertation contribute to this growing body of research and illustrate potentially novel ways for understanding how students come to make use of models, their reason(s) for doing so, and the implications modeling has for student learning. I have shown, for instance, that students' perceptions of models and modeling can greatly influence whether or not they adopt them as problem-solving tools, as well as take the time to construct models *de novo* when encouraged to do so. I would therefore be curious to know if students in Zacharia and Olympiou's (2011) study preferred the physical environment or the virtual environment better, and why. Were they allowed to create their own manipulatives during the experiments or use manipulatives in ways other than prescribed by the curriculum? If not, why not (presuming that laboratory experiments should be constructivist in nature)?

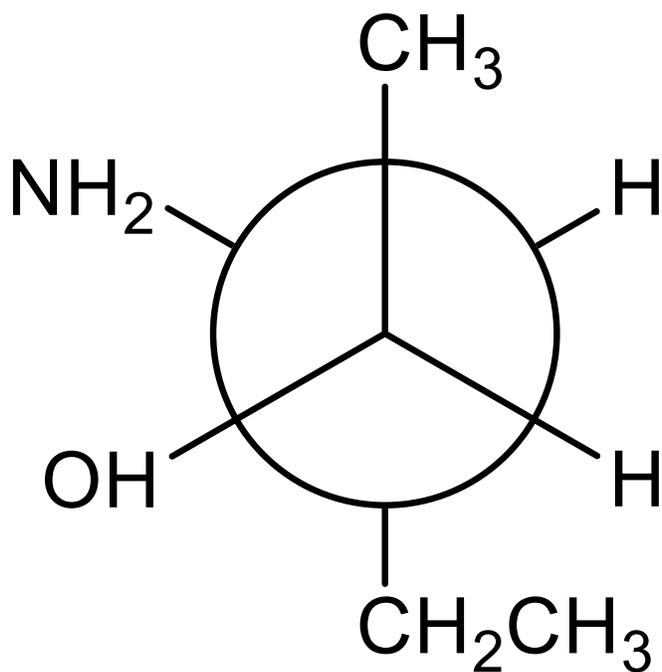
Furthermore, I have demonstrated that faculty's perceptions of models and their use(s) of models in the classroom can also dramatically influence how students subsequently come to use these tools, potentially leading students to perceive models as a waste of time, as confusing, or as less effective for problem-solving than more heuristic approaches. Again considering the broader implications of my work to the science education community, I suggest that the above two experiments could benefit from a similar lens. Were modeling activities routinely conducted/performed in these classes, and, if so, for what purpose(s)? Do other faculty teaching these courses also engage in modeling activities with their students? What factors influence how faculty choose to make use of models in their classrooms? These questions are not meant as a criticism. They were likely outside of the scope of the original studies they reference. However, when taken together, they serve to highlight the germaneness and applicability of my

research to educators in other scientific fields, particularly those who seek to engage in interdisciplinary conversation regarding how to improve students' representational competence through the use of concrete models.

APPENDIX A: Representational Translation Tasks (RTTs)

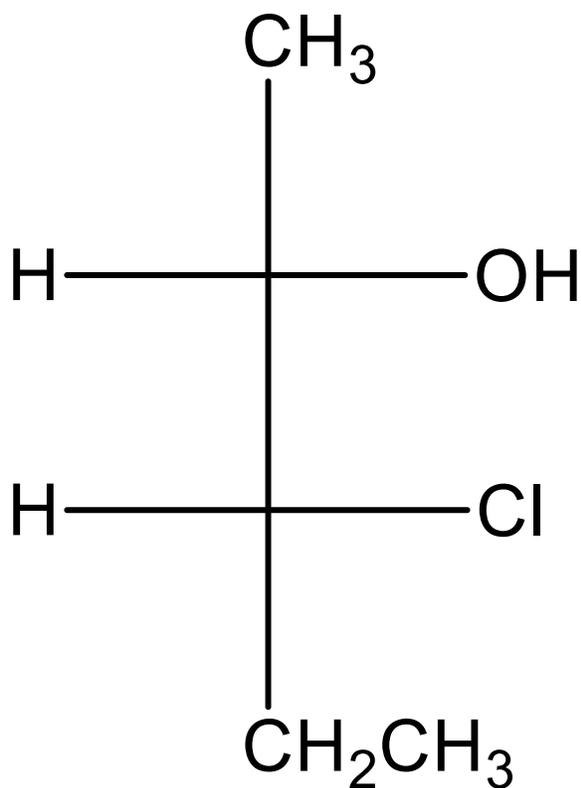
Question 1

Draw the dash-wedge structure that corresponds to this Newman Projection.



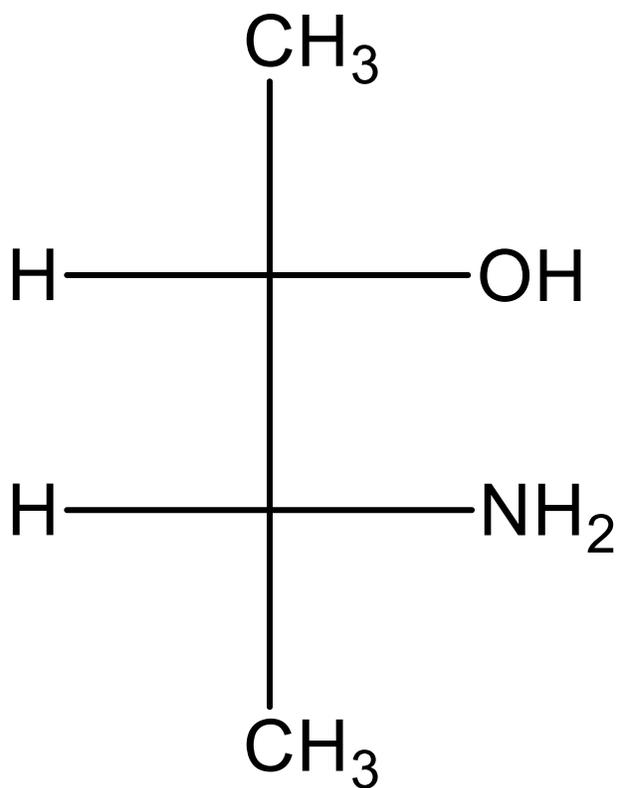
Question 2

Draw the Newman projection that corresponds to this Fischer Projection.



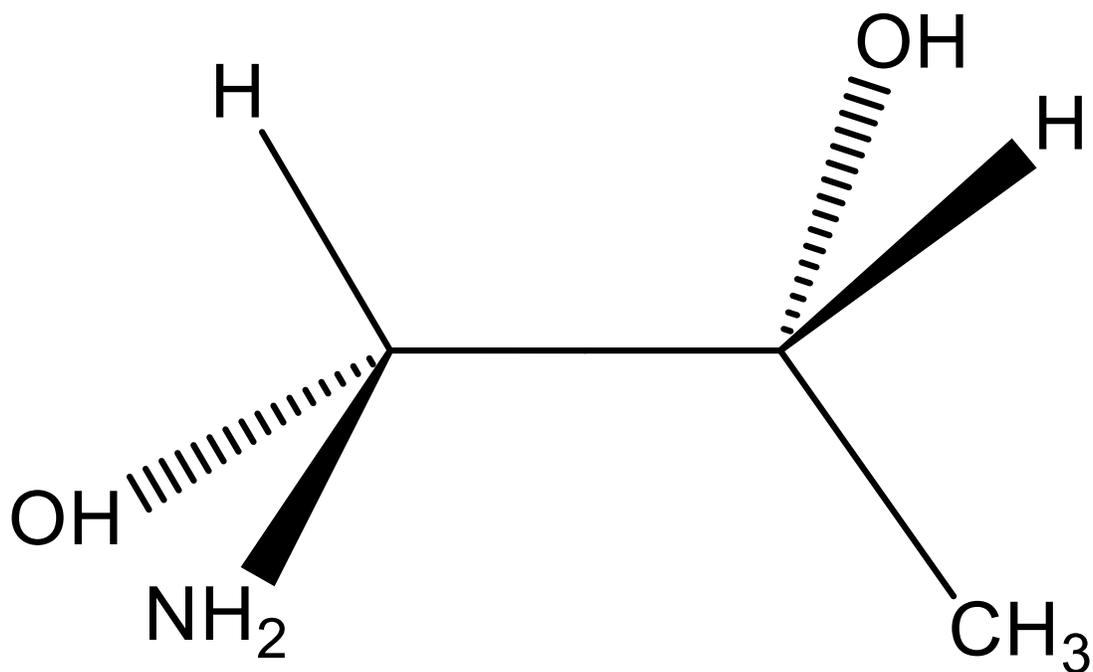
Question 3

Draw the dash-wedge structure that corresponds to this Fischer projection.



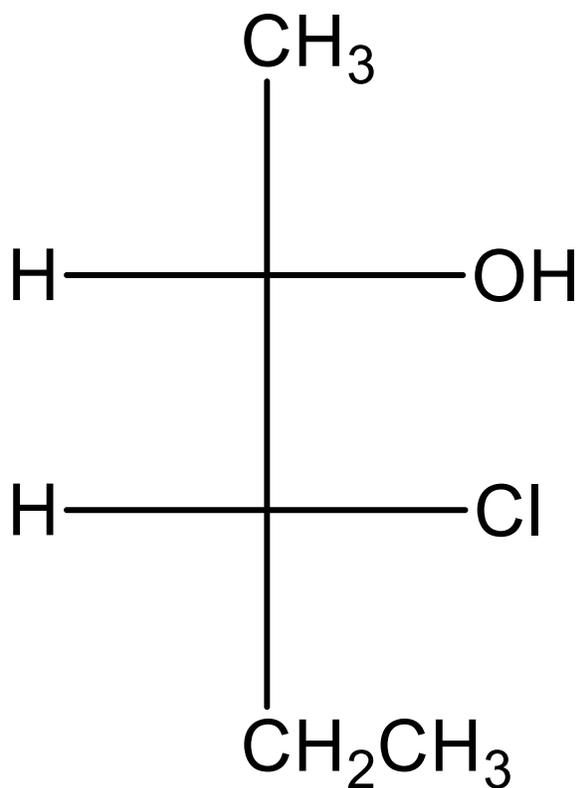
Question 4

Draw the Newman Projection that corresponds to this dash-wedge structure.



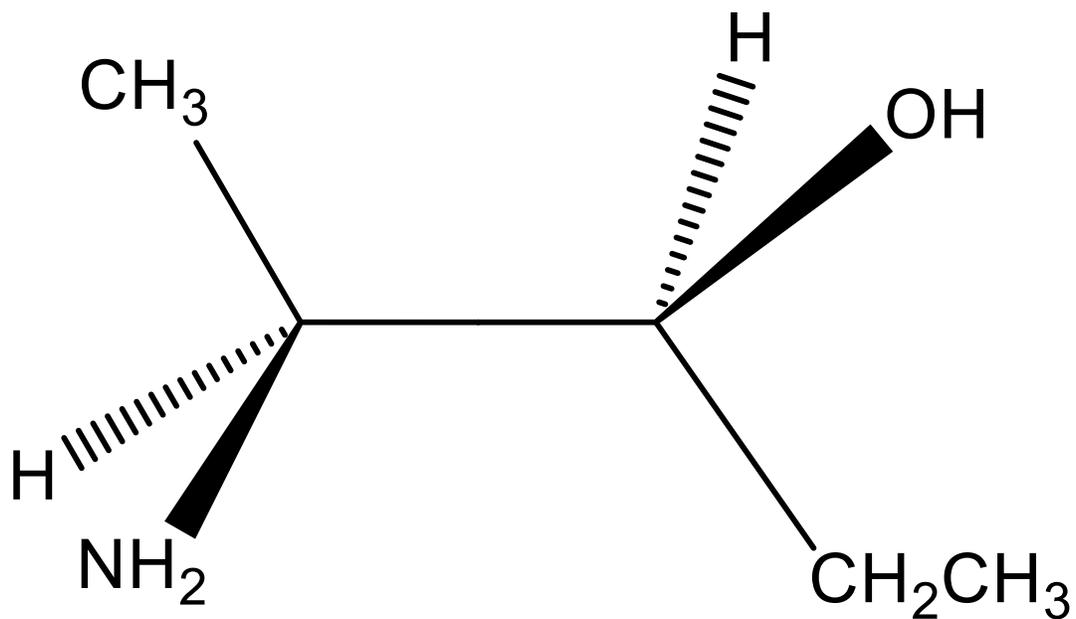
Question 5

Draw the dash-wedge structure that corresponds to this Fischer projection.



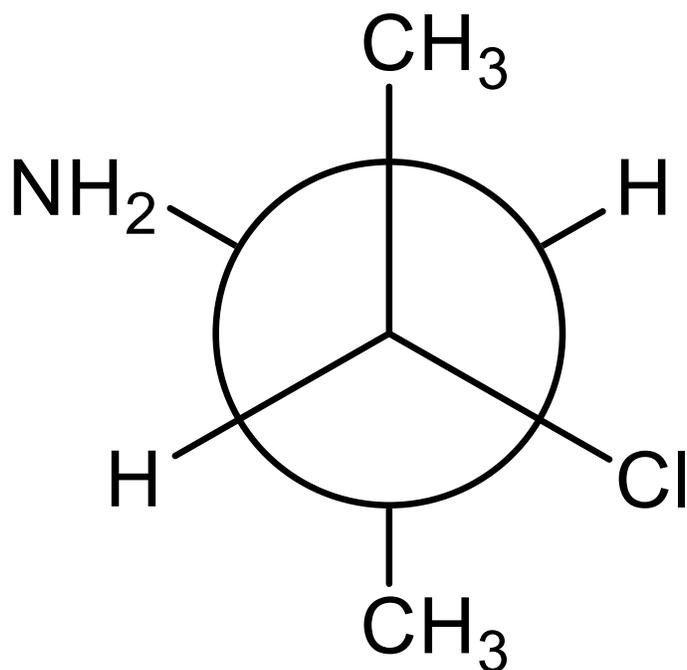
Question 6

Draw the Newman projection that corresponds to this dash-wedge structure.



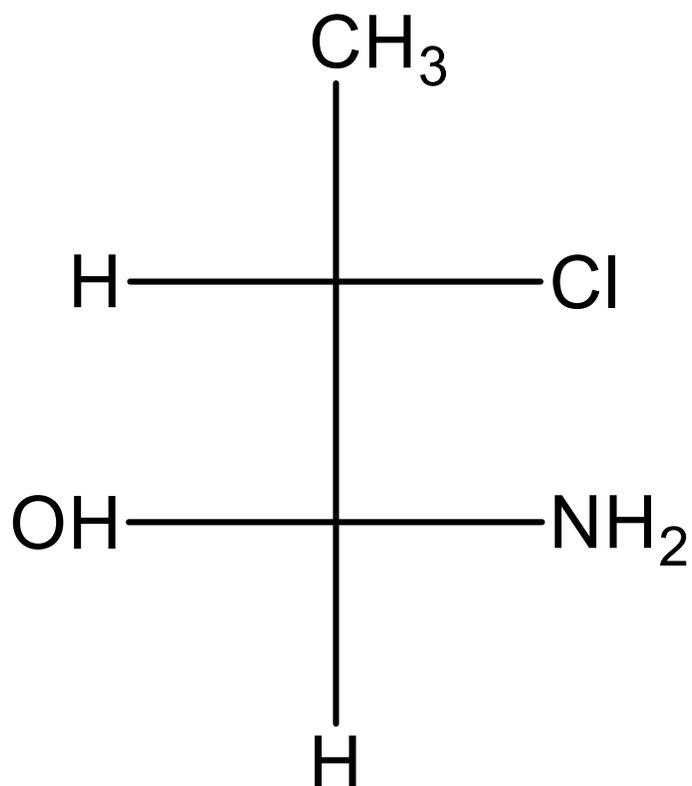
Question 7

Draw the Fischer projection that corresponds to this Newman projection.



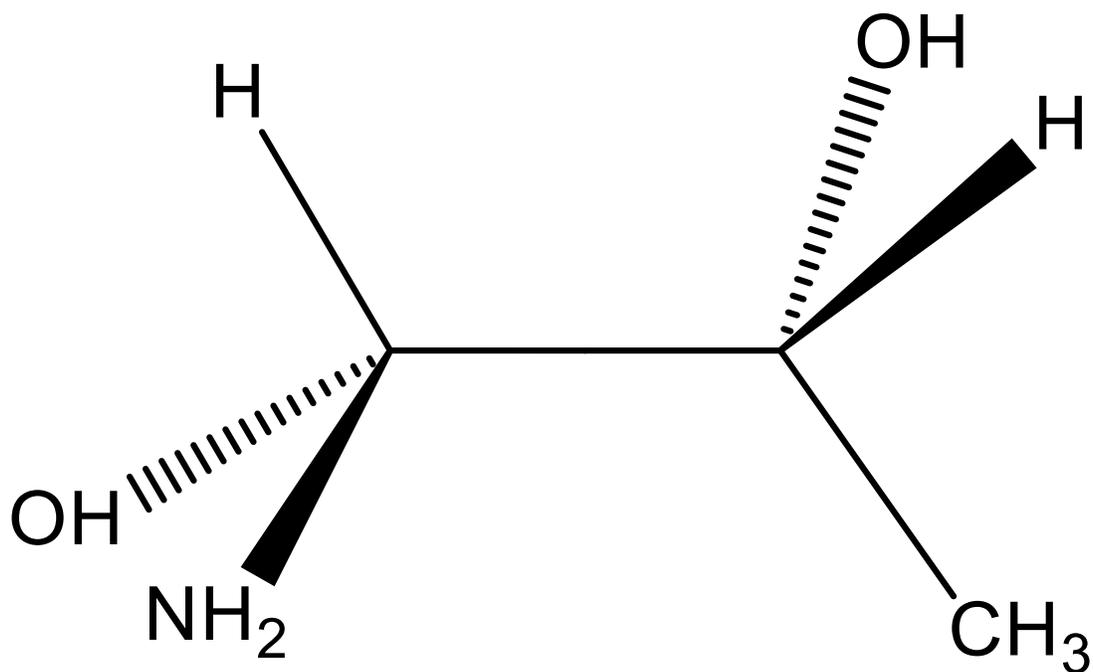
Question 8

Draw the Newman Projection that corresponds to this Fischer projection.



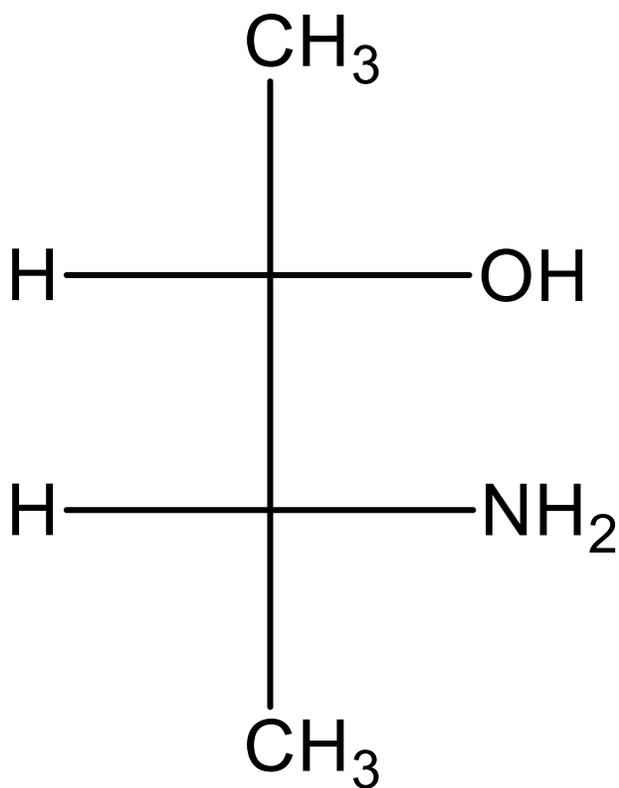
Question 9

Draw the Fischer projection that corresponds to this dash-wedge structure.



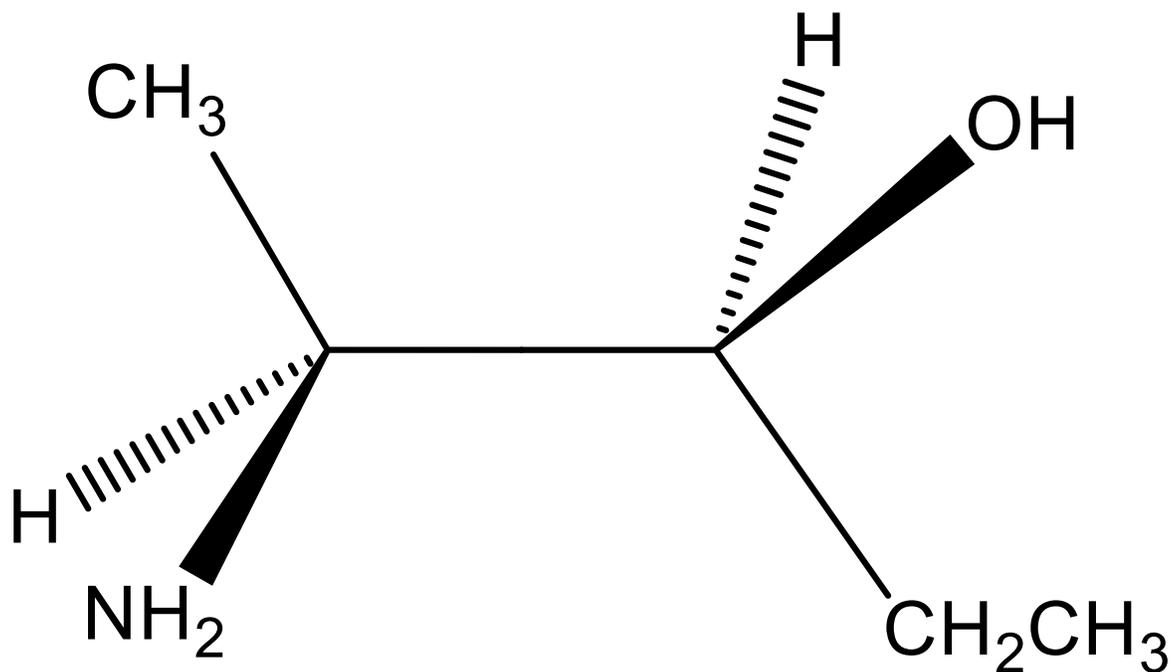
Question 10

Draw the Newman Projection that corresponds to this Fischer projection.



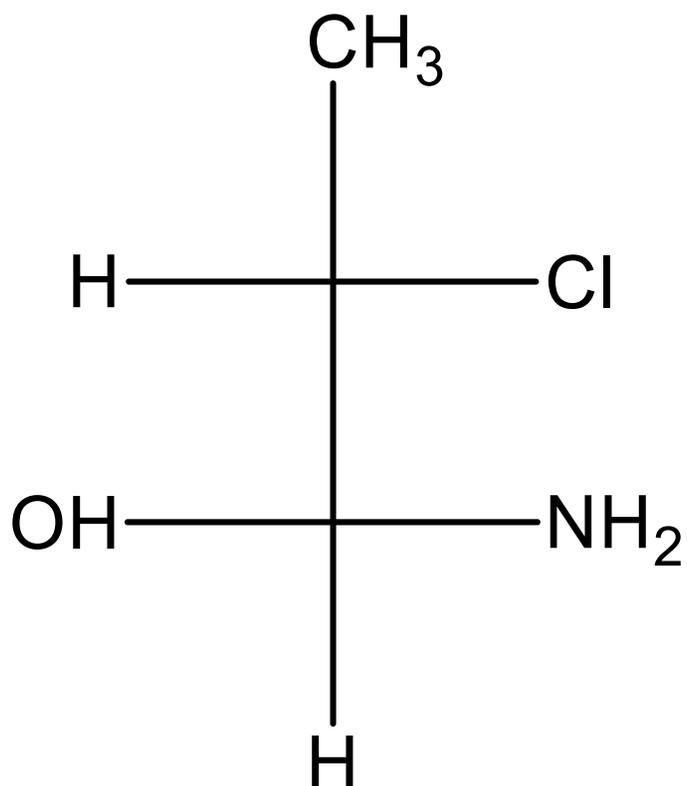
Question 11

Draw the Fischer projection that corresponds to this dash-wedge structure.



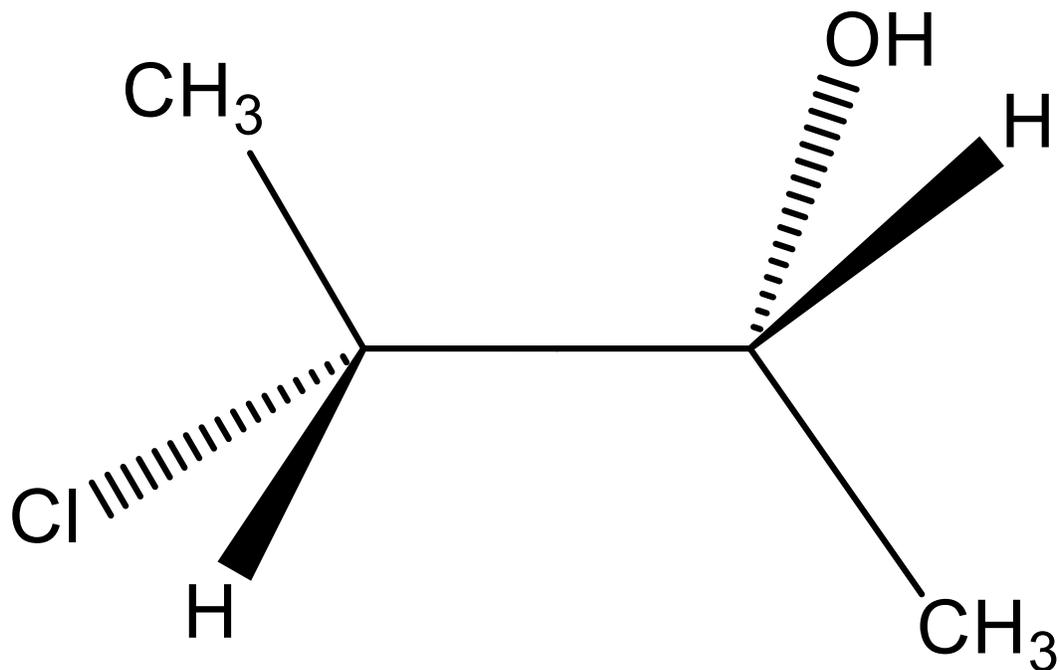
Question 12

Draw the dash-wedge structure that corresponds to this Fischer projection.



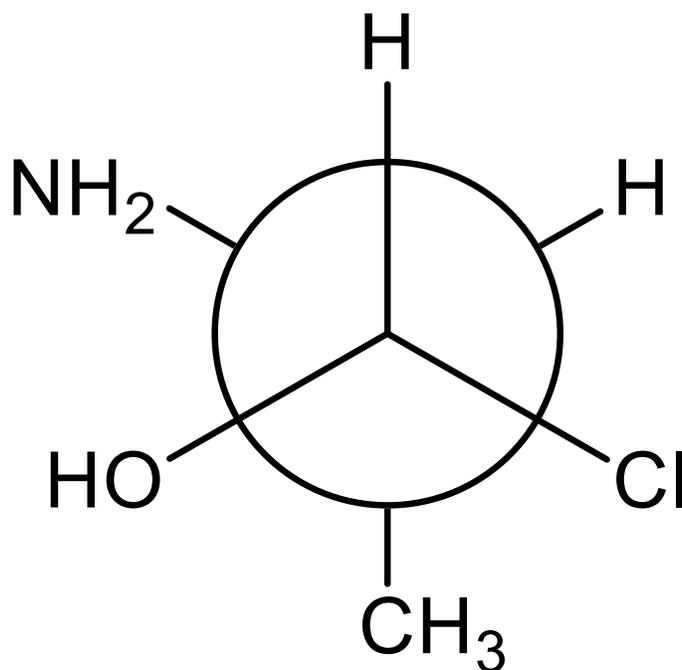
Question 13

Draw the Fischer projection that corresponds to this dash-wedge structure.



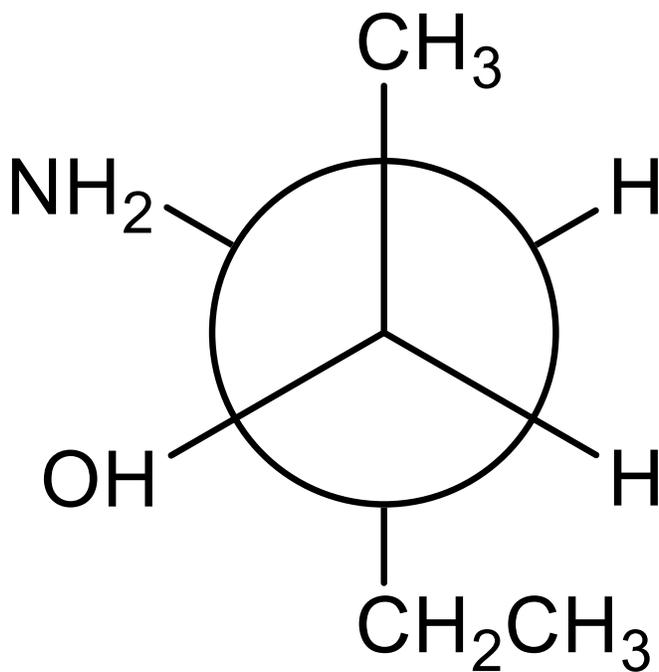
Question 14

Draw the dash-wedge structure that corresponds to this Newman projection.



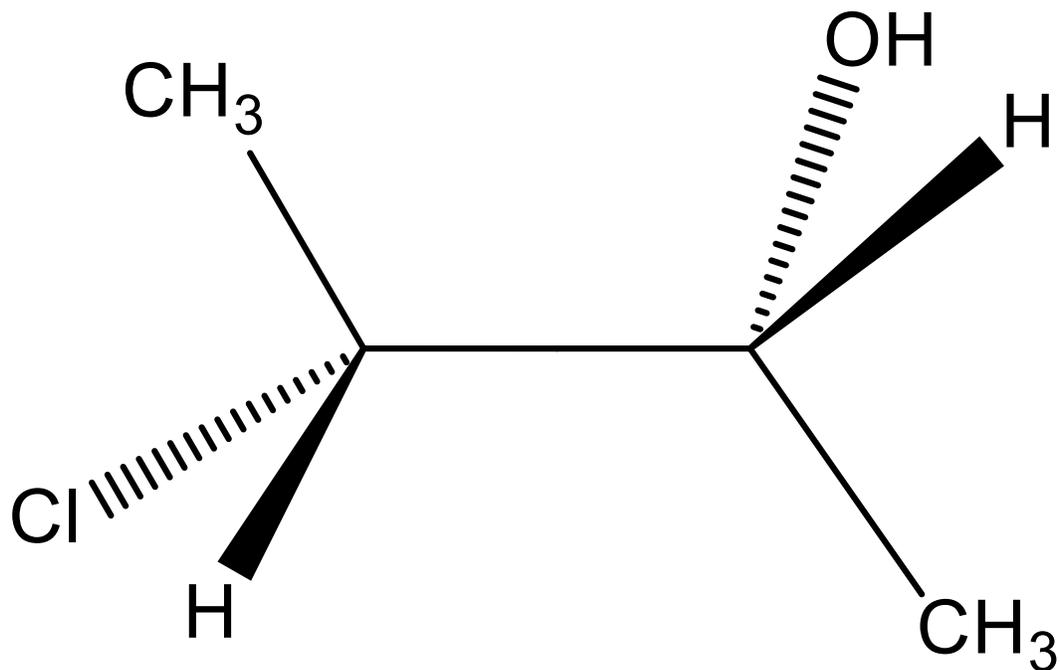
Question 15

Draw the Fischer Projection that corresponds to this Newman projection.



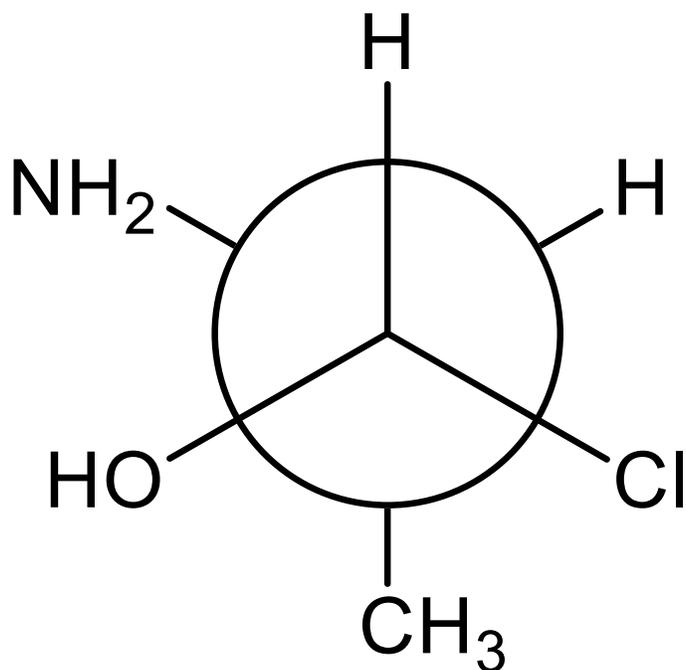
Question 16

Draw the Newman Projection that corresponds to this dash-wedge structure.



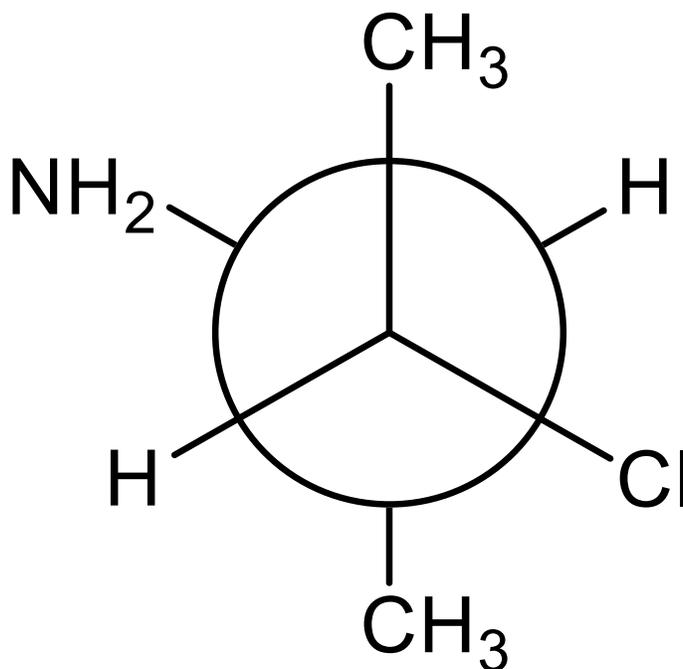
Question 17

Draw the Fischer projection that corresponds to this Newman Projection.



Question 18

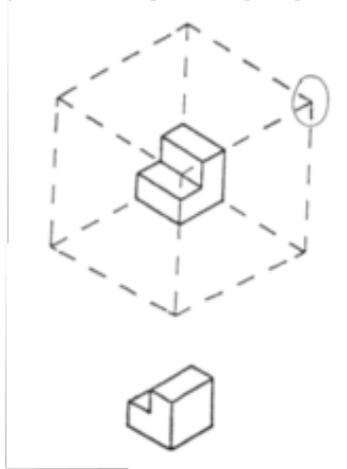
Draw the dash-wedge structure that corresponds to this Newman projection.



APPENDIX B: Sample Item on Modified Visualization of Viewpoints Test

Instructions for Guay's visualization of viewpoints

This test consists of 24 questions designed to see how well you can tell which viewing position a picture of a three-dimensional object was taken from. Shown below is an example of the type of question included in this test.



The example shows an object HOVERING IN THE MIDDLE of a “glass box.” Below it there is a picture of the same object from a new viewing position. You are to:

1. Look at the picture of the object taken from the new viewing position;
2. Imagine yourself moving around the “glass box” to find the corner from which this picture was taken
3. Circle that corner

What is the correct answer to the example?

The correct answer is the upper right corner. Only from there you would have the view that is depicted. Remember that each question has only one correct answer.

APPENDIX C: Video Coding Scheme for Pre-Built vs. Model Building Study

ALIGNED:

Code	Behavior
A	No manipulation
B	Partial alignment to drawing: axis aligned, not components
C	Full alignment to drawing: axis + components
D	Model deictic gesture
E	Diagram deictic gesture
F	Iconic gesture

A – C: Spectrum of model usage. Participant is assigned the highest level of model usage for each trial.

-A: No manipulation of the model.

-B: Aligning the model axis to the target drawing (end on for Newman), but drawing the components in different places than represented on the model for that orientation.

-C: Fully aligning the model axis and components to the drawing. Spatial configuration of the model is reflected in the drawing.

D: Pointing to the model.

E: Pointing to the diagram.

F: Any representative gesture that is not directed at model or diagram.

MODEL BUILDING:

Code	Behavior
A	No manipulation
B	Partial Build (e.g., backbone only)
C	Full Build (full alignment to drawing)
D	Model deictic gesture
E	Diagram deictic gesture
F	Iconic gesture

A – C: Spectrum of model usage. Participant is assigned the highest level of model usage for each trial.

-A: No building or manipulation of a model.

-B: Partially constructing a model. Example: constructing only the backbone of the model, and not fully aligning it to drawing.

-C: Fully building a model, including proper placement of all substituents, and aligning to model to drawing.

D: Pointing to the model.

E: Pointing to the diagram.

F: Any representative gesture that is not directed at model or diagram.

APPENDIX D: Sample Interview Questions for 2D-only vs. 3D-only Study

For those participants that constructed models:

1. Why did you choose to construct and use models to solve these tasks?
2. Were there particular tasks where you found the models to be more helpful, and, if so, which one(s), and why?

For those that did *not* construct models:

1. Why did you choose not to construct and use models to solve these tasks?
2. Ask student to use the modeling kit to construct a model for the initial molecular diagram illustrated in task 18 of the RTT. If the student is capable of doing this, it may suggest that it is not students' unfamiliarity with or lack of knowledge regarding how to construct models, but rather other factors that are mediating model usage (e.g., a cost-benefit tradeoff in which it is too time consuming to construct models and they do not, according to the student, provide any additional valuable information for solving the task).
3. [This prompt precludes that a model for the molecular diagram in task 18 has already been constructed, either by the student or by myself]. Can you show me and describe to me how you might use this model to solve this particular task.

APPENDIX E: Video Coding Scheme for 2D-only vs. 3D-only Study

Code	Behavior
A	No manipulation (either 2D or 3D condition)
B	Match-Align
C	Misalign
D	Gesturing

A – C: Spectrum of model usage. Participant is assigned the highest level of model usage for each trail.

-A: No manipulation of a model or no access to a model.

-B: Aligning the model to match the target diagram.

-C: Misalignment of the model such that it does not match the target diagram (e.g., placing a model of a Fischer projection in a staggered vs. eclipsed conformation).

D: Any deictic or iconic action, such as pointing to the model/diagram.

APPENDIX F: Sample Interview Questions for Faculty Perceptions Study

A. Classroom Instruction

- 1) What role do you believe models have in supporting students' understanding of chemical representations?
- 2) How does your teaching approach align with this belief?
- 3) What, if any, assessments do you currently utilize to examine students' representational competence? In your opinion, is this an important area to assess? Why, or why not?

B. Personal/Professional Attitudes

- 1) How do you make meaning of representations and models, particularly novel ones you may be less familiar with or visualizations you use in your own work?
- 2) How do you believe professionals in the field use representations and models and for what purpose(s)?

C. Obstacles

- 1) Briefly discuss your knowledge of the subject.
- 2) Briefly discuss your experience teaching chemistry and any pedagogical training you may have received. What are your strengths and weaknesses in this area?
- 3) Are there specific obstacles or difficulties you perceive that you feel prevent you from achieving mastery in either knowledge of the subject or in teaching the subject (specifically representations)?

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