Using Multiple Representations to Resolve Conflict in Student Conceptual Understanding of Chemistry

by

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ABSTRACT

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Much like a practiced linguist, expert chemists utilize the power and elegance of chemical symbols to understand what is happening at the atomic level and to manipulate atoms and molecules to effect an observable change at the macroscopic level. Unfortunately, beginning chemistry is often taught in a way that emphasizes memorizing the symbolic representations of equations and reactions without much opportunity to meaningfully connect the observable macroscopic phenomena with an understanding of the chemistry taking place at the atomic level. The compartmentalized manner of chemistry instruction in most chemistry classrooms further nullifies the efficacy of the triplet relationship to connect between macroscopic observations, symbolic representations, and atomic scale views. If symbolic representations are presented as the goal of instruction, rather than as the means to gain understanding, then students will be impaired in developing a coherent understanding of chemical principles.

This dissertation describes the development and implementation of an interview study to examine how undergraduate students interpreted multiple representations of a chemical equilibrium. To establish a baseline of ideas, students first were coached to verbally generate successive representations. They were then cued to think about the chemistry occurring between atoms and ions at the molecular level. Next, an experiment involving a change in states of matter and color was performed which paralleled the symbolic representations. Through self-explanations and verbalizing of conjectures, students were encouraged to explore, interpret, and refine their understanding of the observations related to the chemical symbols presented to them. Finally, with the goal of fostering a deeper understanding of the process of equilibrium, a dynamic visualization of the molecular level was introduced as a tool for helping students connect these multiple representations.

This study revealed that one way in which students develop conceptual understanding and resolve conflicts between different representations of the same phenomena is by verbalizing their ideas as a conjecture (as a verbal explanation to advance towards a hypothesis). Thus, it is proposed that symbolic representations are most effective viewed not as an end goal but as a bridge for connecting macroscopic, visible phenomena with what is occurring at the molecular, invisible level. When the focus on merely memorizing chemical equations and symbols is removed, students can gain a coherent understanding of the meaning available when multiple representations are viewed together.

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To my Savior God – for being the Light.

To my parents – for lighting the fire.

To my dear wife Bess – for nurturing the flame.
(Especially when it seemed like it would go out, you never believed it would go out.)

To my advisors – for showing me how to find more fuel.

To all who mentored, prayed, and cared for all these years –
for encouraging, stoking, and fanning the flame.

To my dear Jesse and Peter and … – for dancing in its light.

Chapter 1: Introduction

The Difficulty in Understanding Chemistry

"The most powerful thing you can do when you're learning chemistry is to zoom down, in your mind's eye, to the molecular level and try to imagine what is going on and in a sense, try to understand the personalities of the reactants and products."

Dr. Roy Tasker - University of Western Sydney (2010)

Chemistry is the study of macroscopic observations that are explained by interactions of atoms and molecules in an unseen world, and requires instruction in helping students to make sense of this invisible world. Yet, the conceptual approach described above is not necessarily the norm in college chemistry instruction. While this could be because of the semantic difficulty in translating words from everyday language, it is more probable that asking students to make sense of *visible* chemical phenomena at the *invisible* molecular level proves to be the more difficult learning process (Wu, Krajcik & Soloway, 2001).

The Triplet Relationship in Representing Chemistry

Chemistry is a difficult subject, because explanations of what is taking place occurs at an unseen level. Johnstone (1991) first proposed the "triplet relationship" as a way to represent student ideas with chemistry phenomena. During the subsequent twenty years, the triplet relationship has been revised to include 1) Macroscopic (observable properties such as state, color, feel), 2) Sub-microscopic (e.g. referred to as atomic and molecular level), and 3) Symbolic (equations and formulas) representations (Johnstone, 1993; Gilbert & Treagust, 2009a). Others have postured that graphs and data tables need to be included as representations (Talanquer, 2011). As a point of reference, "Molecular-level" and "Atomic-Level" are used interchangeably throughout this dissertation to refer to representations at the sub-microscopic level.

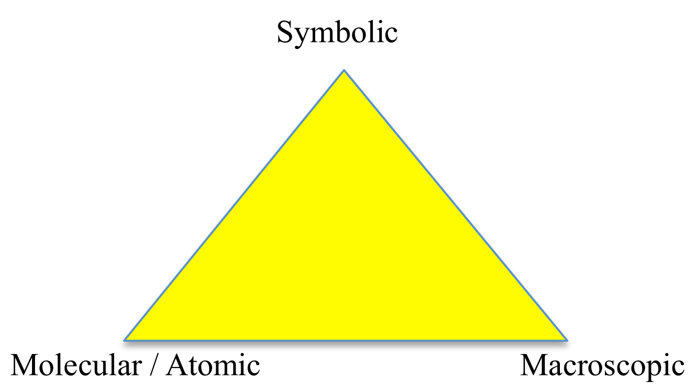

Figure 1: The Triplet Relationship

By contrast, chemistry learners often fail to see that learning a symbolic representation, typically depicted as a chemical formula or set of chemical symbols, is not the end in itself. Nakhleh and Mitchell (1993) pointed out that traditional chemistry curriculum did not promote understanding of concepts at the atomic level, focusing instead on algorithms. (Of course, there are alternative ways to discuss symbolic representations, but this dissertation chooses to bound its consideration around the static chemical symbols representing elements, compounds, and chemical changes that are often written in print in a textbook, on the board, or displayed on a computer screen.) Symbolic representations should be considered the bridge or means to connect between the observable macroscopic representation, and the molecular representation. If students spend much of their time focusing on memorizing chemical symbols, they miss the essence of what is being represented by those symbols.

Interestingly enough, the symbolic representation merely describes in equations, reactions and symbols what is happening with these other two views. (There may even be didactic value in calling them "views" instead of "representations, as both the atomic and macroscopic phenomena are describing phenomena that is visible to chemists. In a sense, a chemistry equation is loaded with clues as to what is happening at the atomic level, as a replacement for the ready ability to look for oneself. Years of studying chemistry equips one to translate rapidly between the symbolic and atomic or macroscopic views. Ironically, the experience of many students is to give up or move on when they are just beginning to grapple with the symbolic representation. They are never helped to harness the power that arises from understanding how miniscule changes at the atomic level results in astounding differences at the macroscopic level.

The Importance of Chemical Equilibrium

Over 50 years of research point to numerous ideas and alternate conceptions students hold when trying to grasp the underlying ideas of the concept of equilibrium (Niaz, 1995; Tyson, Treagust & Bucat, 1999; Voska & Heikkinen, 2000; van Driel & Gräber, 2003; Horton, 2007; Pfundt & Duit, 2009). The teaching and learning of chemistry topics in introductory chemistry courses is one of the most studied and researched areas in chemical education over the last 30 years (McClary & Talanquer, 2011). In a review of high school chemistry topics, "chemical equilibrium" was rated as the most difficult topic in the course for students to understand (Huddle & Pillay, 1996).

Equilibrium is an especially relevant topic for study because of students' rich experiences with it in their daily lives. For instance, equilibrium is at the heart of explaining why only a certain amount of sugar dissolves into a pitcher of sweet tea, or why a metal spoon heats up in a bowl of hot soup. Early chemistry learners may be able to make an observation of a colored precipitate building up in a beaker; nevertheless, they could very well struggle with understanding that the specific chemical symbols used by scientists to communicate with one another a description of the same phenomena.

Since college chemistry learners have presumably accumulated more classroom exposure to the underlying concepts of chemical equilibrium, it might be postured that they should have a deeper conceptual understanding of the phenomena. In comparison, the thought is pervasive in biology students' that the learning of material is related to the accumulation of more information and producing it when called upon (Sandoval & Morrison, 2003; Watters & Watters, 2007). However, more exposure to subject matter does not necessarily translate into more understanding. "Knowledge is not understanding;" it's possible for students to know a good deal of information without understanding the applicability of these isolated facts (Nakhleh, 1992). Thus, this dissertation takes a particular interest in studying chemistry learners at the college level in order to ascertain if instruction affects their ability to resolve conflict among multiple representations.

This dissertation aims to explore how college-level introductory chemistry learners assess and assimilate new scientific evidence that is in conflict with existing scientific evidence. This is particularly relevant in the context of traditional chemistry instruction that often compartmentalizes chemical concepts where instead, overlap might have had a pedagogic advantage.

Theoretical Frameworks

Three frameworks motivate discussion of this dissertation: 1) the MORE Thinking Frame, 2) Knowledge Integration (KI) Perspective, and 3) "Desirable Difficulties."

The MORE Thinking Frame uses the lens of specific metacognitive steps to examine how learners Model, Observe, Reflect and Explain a chemical phenomenon (Tien, Rickey & Stacy, 1999; Tien, Teichert & Rickey, 2007). In the first step of the MORE Frame, students discuss their initial ideas, requiring them to consider the chemical system as a whole. Observing the results of experiments allows them to test their model. After reflecting on their ideas in light of the new evidence, they then need to refine the model that they had come up with. Through prompted reflection, students revise their models to explain why certain chemical phenomena had occurred. This process allows students to begin with their own ideas, and then reflect on these ideas to allow them to make sense of what they had observed. Students who engaged with the MORE Thinking Frame exhibited a greater likelihood of monitoring their own thinking (Mattox, Reisner & Rickey, 2006). Thus, they would be more likely to generate their own ideas, reflect on voiced ideas, compare/contrast between ideas and ultimately reflect on these ideas

The Knowledge Integration (KI) perspective is governed by four meta-principles: 1) making science accessible, 2) making thinking accessible, 3) helping students learn from others, and 4) promoting autonomy and life-long learning. Thus, learners are viewed as "developing a repertoire of ideas, adding new ideas from instruction, experience, or social interactions, sorting out these ideas in varied contexts, making connections among ideas at multiple levels of analysis, developing more and more nuanced criteria for evaluating ideas, and formulating an increasingly linked set of views about any phenomena" (Linn, 2007). This perspective has led to the development of the KI Instructional Pattern, involving helping students to 1) elicit ideas, 2) add normative ideas, 3) distinguish among alternate ideas, and 4) reflect on connections among these ideas. Since ideas play a primary role in this framework, the collision of alternate ideas or concepts with normative ones is crucial, as this presents opportunities for students to use valuable reasoning strategies for sense-making. (Linn & Eylon, 2006).

The third consideration is in creating moments of 'desirable difficulty' - a series of events of conceptual conflict providing an opportunity for students to challenge their scientific concepts (Bjork, 1994; Chiu, 2010; Linn *et al*., 2010; Clark & Bjork, 2014). It is important for students learning representations to be able to access the targets of those representations even when contextual clues change. One novel way is to introduce contexts that interfere with a students ability to simply recall a memorized statement, and forces them to reconcile seemingly conflicting ideas, learners may actually think more deeply about a subject. Though he or she may not be aware of it, a student's struggle through such a conceptual difficulty is actually a desirable learning event.

This desirable conceptual difficulty is also similar to the idea of 'cognitive dissonance,' recently revisited by Linenberger & Bretz (2012) in the context of biochemistry education. Cognitive dissonance is described as a psychological state where the learner's attitudes, beliefs, or behaviors are at odds with one another – when new information is encountered that does not fit into an existing construct possessed by the learner. However, this conflict creates a motivation for a learner to resolve the inconsistency, by either choosing to reject the new information or adapting the existing construct to fit the new information.

All three frameworks place the student and their ideas at the forefront of the analysis. As students are encouraged to verbalize what they know, their self-learned and self-experienced ideas begin to intersect with normative or canonical scientific ideas. While sometimes confirmed in their understanding, at other times, they find themselves needing to reconcile conflicting ideas. As they seek to make sense of this repertoire of ideas, they may revise and connect these ideas until they reach a level of understanding. At other times, the challenge is too great, and they leave the topic confounded and their conflict unresolved. This could especially be true with such a multi-layered concept as chemical equilibrium. Thus, intentionally introducing a "desirable difficulty" causes students to pause and focus on the learning event, opening the opportunity for developing in their conceptual understanding.

Principle of a Conjecture[1]

The hypothesis is that conjectures are needed to resolve the conflict of ideas when students are faced with contradictory evidence. For the sake of the analysis of student data, the following definition is proposed: Conjectures are the verbal expressions of initial ideas of students, often as a starting point in the formation of a hypothesis. While not as rigorous or even as informed as a hypothesis, a conjecture nevertheless is seeking to explain an observation, a phenomena, with a view to reconciling conflicting information. The act of conjecturing is intimately related to the process of developing understanding, and can even lead to a more connected understanding. Without advancing a hypothesis or verbalizing their ideas as conjecture, even if there is seemingly adequate prior knowledge, students have less success in connecting their ideas across different representations.

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[1] As a point of clarification, my usage of the term *conjecture* has nothing to do with the recently described technique for conceptualizing design research proposed by Sandoval (2014). His goal is to describe a way to conceive of and carry out research on learning environments.

It is proposed that during the course of the interview study, students will need an opportunity to reconcile macroscopic observations with symbolic representations and atomic scale views. For example, in a situation where a normative scientific explanation is needed to explain some observed experimental evidence, a student would have to be confident enough with their ideas to verbalize them, and familiar enough with the observed phenomena to make scientifically reasonable statements. This also would imply that the individual would have to have enough prior knowledge and understanding of the material to make a conjecture. A strong conjecture is borne out of good observations, and a consideration of various possibilities for explaining those results.

It is not necessary to have a complete understanding of evidence to make a conjecture. Rather, it is like a verbalized statement indicating a preference in explaining a particular scientific phenomenon. While a conjecture is similar to a hypothesis, it is not necessarily persistent enough that a student revisits the conjecture to test its validity. Conjectures are not weighed or evaluated for their correctness, because they are more like educated guesses than statements of fact. However, the ability for a conjecture to be evaluated or revised is crucial in helping students reach a level of deeper conceptual understanding.

Dissertation Overview

Chapter 1 guides the reader to explore the rationale, the motivating questions and the potential usefulness of this study. This study focuses on one aspect of the chemical conceptual understanding of post-secondary college chemistry learners. Chapter 2 follows by 1) describing student ideas about chemical equilibrium, 2) outlining the significance and usefulness of the triplet relationship and the linking of multiple representations as based in the existing literature.

This methodology chapter (Chapter 3) introduces the semi-structured interview study which provides the main body of research data. This chapter answers questions such as “Who are these students?” “What was asked during the actual interview study?” and “What type of data was gathered?” The goal of the interview was to elicit from the subjects as many conceptions as possible, giving them opportunities to consider multiple ways to interpret a given symbolic representation. All six steps of the interview study are described in detail, as well as the rationale for including them. This chapter also highlights some of the conceptual conflicts that students encountered in the course of the interview.

In Chapter 4, the distinction between a dissolution and dissociation model of understanding equilibrium acts as a lens into how students are using evidence to inform their model of equilibrium. Symbolic chemical representations are often used in instruction to describe chemical phenomena, but in this case, the physical, observable evidence seen by students apparently contradicts the symbols. As a solid dissolves in a liquid and produces results that are unexpected, a conflict is introduced where there is a mismatch between the representations presented to students. This specific conflict was primed through the use of a symbolic representation, and can be ultimately resolved through guiding students to see that both models are taking place. Though this is not described in the written equation, instructors can learn to prime students appropriately with the correct models.

Chapter 5 examines yet another dilemma in student understanding related to the disconnect between macroscopic observable evidence, and a student's understanding of what is happening in terms of concentrations of molecules. By recognizing that color can be used as a macroscopic property to link to what is happening at an atomic level, student's ideas can be probed to expose their difficulty in understanding that color should be considered as a property of individual molecules.

Chapter 6 serves as a summary to enlighten the reader as to the behavior of conjecturing in being meaningful in bringing about student understanding. Four different pathways reveal the effect of conjectures on aiding students in the course of the interview study. Interestingly, it is not so much the content of students' conjectures as it is the act of conjecturing and willingness to adjust the conjecture that differentiates successful students. Thus, one goal of instruction could be to help students make conjectures to connect observable properties or observations to atomic-level representations.

In the concluding chapter (Chapter 7), the reader is brought back to the triplet relationship and the three levels of representation in chemistry. The symbolic representation is highlighted as a means by which observable, experiential chemistry can be linked to understanding the behavior of atoms at the molecular level. This interview study provides insight into specific student ideas, and allows them to be characterized in a systematic way that is useful for design of instructional strategies. In addition, student decision-making is referenced as in the context of the heuristics literature as a possible direction in which to focus further studies.

Chapter 2: Motivating Questions

The goal of this chapter is to illuminate the theoretical perspectives motivating the design of the interview study and constraining the interpretation of the analysis.

Research Question 1: Student Ideas about Equilibrium
What prior knowledge is activated when students are trying to make sense of a symbolic chemical representation describing equilibrium?
How has typical chemistry instruction impacted student ability to understand the common factors in representations of chemical equilibrium?

Because equilibrium spans multiple areas of chemistry with many potential access points through instruction, it is a fruitful area for investigating how students develop a connected and integrated understanding. For a number of reasons, chemical equilibrium is also the most difficult topic for students to understand. On the one hand, it is a topic that is abstract (Ben-Zvi, Eylon & Silberstein, 1988), but on the other hand, many misunderstandings arise from confusion over the semantics of words used in traditional vocabulary (Bergquist & Heikkinen, 1990). Much work on student conceptions detail the plethora of right and wrong ideas that students can hold about equilibrium (Garnett, Garnett & Hackling, 1995; Tyson, Treagust & Bucat, 1999; Voska & Heikkinen, 2000; van Driel & Gräber, 2003; Horton, 2007).

On the conceptual level, instruction has allowed for ample opportunities to learn the facts of chemistry, but also has potentially opened the door for many non-normative conceptions to creep in. They may think about equilibrium having a forward and reverse reaction, a concept taught them at the junior high and high school levels, but perhaps never assimilated. They may incorrectly extend or apply this idea to think that the forward reaction and reverse reaction causes chemical equilibrium to oscillate like a pendulum (Bergquist & Heikkinen, 1990). Yet, no one would argue that the problems in learning chemistry are due to ideas held by students, but due to the conclusions students make as a result of the knowledge they do have. As summarized so succinctly by (Smith, diSessa, & Roschelle, 1993), "misconceptions are faulty extensions of productive prior knowledge."

According to constructivist ideas about student learning, student thinking builds on prior knowledge, whether or not that knowledge is actually productive in leading a student towards understanding (Bodner, 1986). Occasionally, there is even no prior knowledge in an area for this new information to conflict with (Zoller, 1996). Much of the typical instruction in chemistry that takes place in the first two years of college, and especially in organic chemistry, reflects a pattern of thinking where students are just containers to receive the content dispensed by their instructors. It is hard for students to work with ideas with which they have no prior experience (Ben-Zvi, Eylon, Silberstein, 1988) This model of the instructor as the fountain of knowledge dispensing into the empty vessels of chemistry learners de-emphasizes the importance of student's ability to actually understand a concept.

The tradition of lecture-based college chemistry instruction has not been to take the time to consider prior thinking, but rather focuses on conveying content or procedural algorithms (Nahkleh, 1993). The implicit goal seems to be memorizing material with the view that the student studying on their own will mysteriously make the links necessary to change their thinking to expert thinking. By the time students are taking college chemistry courses, they have accumulated years of content knowledge exposure and may have attempted to incorporate many ideas into their thinking. However, as Nakhleh (1992) pointed out, “Knowledge is not understanding;” it is possible for students to know a good deal of information without understanding the applicability of these isolated facts.

Considering the amount of instruction upper level college undergraduates have undergone in their field, one might be quick to suggest that these students have conceptually connected deep ideas. However, mere exposure to the subject matter does not translate into conceptual understanding. Conceptual understanding only includes understanding that is beyond rote memorization of facts and algorithms (Claesgens, Scalise, Wilson & Stacy, 2009). Chronological progress in their education, though there is more exposure to chemistry content, does not necessarily correspond to students making links across ideas or concepts.

As an illustration, a typical general chemistry class in the early 21st century is taught in a large lecture hall with accompanying head-nodding and note-taking. An instructor stands at the front of the class, guided by a whiteboard, powerpoint slides, or Elmo for drawing notes. At many post-secondary institutions, these classes are typically taught in a way of assimilating, even memorizing, information, formulas, and algorithms that are then fed back to the instructor in some type of assessment. Since textbooks are typically organized into approximately 20 chapters, the majority of which are “covered” in a first-year college course in chemistry, the assessment might cover a chapter or a cluster of chapters. It is thus possible for a typical chemistry learner to develop individual “card catalogs” of facts, phenomena, and ideas that are not explicitly connected to one another during instruction.

The literature clearly points out that this material is not useless. Chi (2005) pointed out that conceptions may be quite solidly entrenched in students and not easily changed. Sadler (1998) recognized that these conceptions not only don’t go away easily, but actually can be useful for students as they think about material. Hammer (1996) offered that the misconceptions perspective "in focusing only on how student ideas conflict with expert concepts...offers no account of productive ideas that might serve as resources for learning." Smith et al (1993) revisited several central assertations of misconceptions, demonstrating the inherent value in students’ prior knowledge as they make sense of newer material. Thus, rather than spending lots of time to diagnose prior conceptions merely for the sake of labeling them, there is the need to consider how they are necessary for students constructing their own thinking.

Songer & Linn (1991) remind us that it is also important to recognize that the process of forming scientific ideas is different from a scientific finding itself. As a result, confronting students with new information in the face of prior knowledge is necessary for scientific thinking to take place. Reif & Larkin (1991) pointed out that students may prefer to look at phenomena through the lens of every day reasoning. Hapkewiecz (1991) presented some simple demonstrations to help challenge students' ideas. Finally, Talanquer (2006) brought forth that many students start at a common-sense level of chemistry, trying to relate their everyday experience to the new material that is brought to them. This line of thinking culminated in the "Perspectives of Chemists" framework as elucidated by Claesgens et al. (2009), acknowledging student thinking as a progression from a basic experiential "Notions" level to higher levels that result in links and connections across topics.

In addition, a convincing amount of work has been done to demonstrate that student ideas are largely context dependent. Fragmented understanding has been demonstrated in physics education (diSessa et al, 1998), where student understanding is often not "contextually coherent" or coherent across different contexts. In chemistry learning, when students were asked to provide molecular-level ideas regarding aqueous solutions, their explanations varied depending on the context in which the task was introduced (Teichert & Stacy, 2002). Other work has shown that students may overlook even the most "glaring inconsistencies" when conceptions are tied to certain contexts (Pressley et al., 1992). Such studies illustrate that students can hold different, often contradictory, macroscopic ideas with which they reason depending on the context of a problem. One proposed resolution in quantum chemistry was to encourage instructors to find ways to facilitate connections to a new context, by giving students familiar contexts to activate relevant ideas (Taber, 2004). This would set the stage for students faced with an unfamiliar interview study; context surely matters for understanding.

This section has provided a frame for the issue for the second research question by investigating the content knowledge that a student has to have in order to form deeper connections in their understanding. Thus, it should not necessarily be assumed that students with more exposure and presumably more content knowledge would be able to more fluently make these connections.

Research Question 2: Symbolic Chemical Representations

How can the triplet relationship be used by learners to illuminate and identify a mismatch between symbolic chemical representations and macroscopic observable characteristics?

Helping students to understand the unseen realm of chemistry involves showing them that chemical phenomena occur on different levels of representation: the macroscopic (observable), the submicroscopic (molecular and atomic), and the symbolic (equations, chemical formulas, and mathematics) (Johnstone, 1991; Gabel, 1999; Gilbert, 2008). While unable to represent all of chemistry, symbols have a function in bridging to their respective meanings (Hoffman & Laszlo, 1991). Palmer (1978) indicated that a representation is "first and foremost, something that stands for something else." This implies that there are two worlds that need paying attention to, a represented world and a representing world. It must be asked, "What aspects of the represented world are being captured in a representation, and what aspects of the representing world are doing the representing, and how are these two correlated?" The referring representation must mean the same thing to all those who use it in order for the referred phenomena to have any meaning (Sherin & Lee, 2005). While experienced chemists can readily accept and work within this "triplet relationship," novice chemistry learners struggle greatly with this (Kozma, 2003).

Typical Instruction

Because so much of chemistry is based on abstract and unobservable aspects of chemical phenomena, much instruction takes the place of merely manipulating a particular representation on the symbolic level, without ever considering how this relates to the experiential realm (Chittleborough & Treagust, 2007). Typical chemistry instruction focuses greatly on the relationship between the symbolic and submicroscopic representations, often disregarding students' experiential ideas about the material (Kozma & Russell, 2005). Yet, ironically, it is the intersection of these three that is most crucial for developing understanding for learners. Indeed, the use of symbolic and molecular-level representations have their origin in students trying to compare analogous sensory experiences at the macroscopic level (Hoffman & Laszlo, 1991). While instructors might use a variety of representations to refer to atomic objects and processes of chemistry, they may not be so explicit in drawing the connections among them.

As an example, examine some of the shortcomings in traditional instruction using $Cu + O_2 \leftrightarrows CuO$. Substantial time could be spent by instructors teaching students how to interpret an equation such as $Cu + O_2 \leftrightarrows CuO$. If the student is taught that each Cu should represent copper, each O_2, molecular oxygen, and each CuO, copper oxide, then an instructor might be content with student understanding of the symbolic notation. Going further, the instructor would show that each Cu represents a mole of Cu, each O_2 a mole of oxygen and each CuO a mole of copper oxide and that the absence of any coefficient indicates that there is only one unit. This type of instruction is not trivial or unnecessary; it needs to be taught in every introductory chemistry classroom.

Learners who have difficulty understanding information at such a definitional level might not be able to go on to deeper constructs (Cook, Wiebe, & Carter, 2008), instead lingering while trying to decipher the meaning or patterns in the various letters. Using the idea of equal amounts to elaborate more on a submicroscopic representation, an equation like the one above implicitly points out the need to keep track of the amount of each substance present. By writing the symbolic notation in an equation and borrowing from math, the idea of a balance is implied. Instructed students would recognize that there are two moles of oxygen on the left side and one mole of oxygen on the right. Thus, the skill of balancing an equation would be taught to help students keep track of equal amounts of substance. With training and more exposure over the years, students could become quite adept at balancing complex equations with multiple substances present. However, there is clear evidence that balancing chemical equations can be done with little or no understanding of what the equations represent on a molecular level (Yarroch, 1985). Students who succeed in learning this aspect of chemistry may just have been very good at solving algorithmic problems, even developing and memorizing mnemonics for organizing their thinking about chemistry (Nakhleh, 1993). Thus, it would be quite probable for a student to be able to balance an equation, and even predict the change based off of patterns that would occur with a given reaction, but not understand why this occurred.

On a different class day (perhaps 80 pages later in a typical textbook) students might be led back to a similar reaction and would be asked to describe what would happen to the reaction if more oxygen were added. This would be their introduction to LeChatelier's Principle: a reaction will respond to any stress by shifting in the opposite direction to relieve that stress. However, rather than asking what this would look like at an atomic level, students would be asked to manipulate the symbols to take account of a change. While a fruitful way to consider qualitative changes to a reaction (and a valid predictor in ~90% of the cases of how a reaction will respond), LeChatelier's Principle could also be taught and learned in an algorithmic fashion that failed to take into account what was happening at an atomic level. This has led to findings such as those by Wheeler and Kass (1978) noting that nearly all of their high school chemists were guilty of misusing LeChatelier's Principle, not realizing that it could not be applied in all situations. In another sample, Quilez-Pardo and Solaz-Portoles (1995) found that teachers applied it where it did not apply, resulting in incorrect predictions.

In a discussion with chemistry graduate students at UC Berkeley, several pointed out the problematic nature of the equation $Cu + O_2 \leftrightarrows CuO$, as the phases (solid, liquid or gas) of the matter were not specified. While it's perfectly possible to perform some manipulations on an equation like our learners, additional data about the condition of the reaction such as the heat of the reaction or the properties of surface chemistry would be necessary in order to conceptualize this reaction actually occurring in nature. When the discussion turned to copper tarnishing (like a blackened penny) or copper smelting (purifying metals from extracted ore), these graduate students were immediately able to draw connections between the macroscopic properties and the submicroscopic representations. Student ability to do so would actually correlate with student prior knowledge of the underlying concepts (Keig & Rubba, 1993; Seufert, 2003).

LeChatelier's Principle

These links are easy for experts to make, but they are not typically taught or emphasized in instruction. Instead, students become experts in distinct compartmentalized domains of chemistry representations, such as balancing equations or predicting the change in a reaction using LeChatelier's Principle, without developing understanding (Garnett, Garnett, & Hackling, 1995; Quílez-Pardo & Solaz-Portolés, 1995). Understanding would appear to be related to the ability to look at an equation and recognize that the same symbols that are describing the atoms present are also able to depict how they are interacting.

The polished "products" of this type of instruction are not just undergraduates, but eventually graduate students, still guilty of failing to make these types of connections (Bodner, 1991). It would be fair to extrapolate that some of the professors and instructors leading university chemistry classes (former graduate students!) are also perpetuating this failure. In fact, university chemistry faculty might even believe that mere subject matter instruction alone will help students connect across multiple representations. They might encourage first-year students to "keep at it!" in spite of a student's lack of understanding. These well-intentioned teachers hope that at some later point in their instruction, there will be an opportunity to think more deeply about the material or to draw connections among ideas. Yet, that day may never come in the rush to cover an entire textbook's worth of material in a semester. Students who "don't get it" drop the class and possibly even reconsider their college major and life goals; others persevere until the next midterm or even the next class before giving in.

Research Question 3: Conceptual Understanding through Multiple Representations
How can symbolic chemical representations be used to successfully link and connect macroscopic observations with atomic-level representations, thus resolving student conceptual difficulty and promoting a richer understanding of the chemistry taking place?

Representational Competence
Chemists can see expressions with different surface features as all representing the same principle, concept, or chemical situation, and they can transform the expression of a chemical concept or situation in one form to a different form. Likewise, they can take a representation with surface features, and read out different underlying principles. This ability has been referred to as "representational competence" (Kozma & Russell, 2005). However, this does not necessarily mean that novice learners are not able to make a connection among 1) the symbolic notation, 2) what they were able to observe (macroscopic), and 3) what is actually happening at an unobservable level (submicroscopic). Thus, those authors have developed a measure of one's ability to translate among representations as described by a number of skills, rather than a mere measure of science content knowledge.

Successful chemists must develop skills associated with describing phenomena, discerning and selecting between representations, as well as communicating features and patterns of representations with words. Making connections across representations is essential to representational competence, as well as explaining the relationship between these representations. Recognizing that representations are not reality, but correspond to phenomena, is a key epistemological component of working with representations. Finally, the user must be able to support claims, draw inferences and make predictions as evidence to communicate amongst a community of chemists (Kozma & Russell, 2005). This could be further strengthened through diSessa's (2004) principles of metarepresentational competence, which include the ability of students to generate, interpret and critique representations.

In a sense, the learning of chemistry subject matter requires learning the language of chemistry in order to socialize amongst chemists. Yet, the essence of being a chemist is not merely to understand or even speak the words of chemistry, but to understand that the words are describing and painting a picture of an unseen reality. This unseen realm is described and communicated through lots of representations and the connections among them. Difficulty in using and interpreting these representations may not be due to individual mental deficiencies, but inexperience with conventions or unfamiliarity with a physical context in which they are being used (Roth & McGinn, 1998).

There is a distinction between the subject matter competence of students as measured by student ability to memorize and recall chemical symbols, and their representational competence as chemists (Kozma & Russell, 1997). The expected norm is that students with a high subject matter competence would be able to fluently make connections across representations. For example, it is possible to strengthen and improve representational competence, even while subject matter competence is being developed. Kozma (2003) pointed out expert chemist's ability to coordinate features within and across multiple representations to reason about their research and negotiate shared understanding based on underlying entities and processes." At the same time, novices have difficulty connecting between representations, often resorting to looking for algorithmic approaches to manipulating symbols. Thus, it is worth looking at how multiple representations are used to make meaning.

Usefulness of Multiple Representations
Harrison and Treagust (2000) specifically targeted chemical equilibrium when arguing that the more abstract a phenomena, the more likely it would be to utilize multiple models to represent it. They argued that a series of simplified models could be used to explain key ideas one at a time. Thus, the following two frameworks were examined to see how symbolic representations could be consulted as the core representations in helping students resolve conceptual difficulty.

Ainsworth's DeFT (Designs, Functions, Tasks) framework proposed three main tenets for how multiple representations function in learning. 1) Multiple representations support learning since they allow complementary processes or information to be presented. 2) At the same time, a representation could be presented in such a way as to constrain interpretation of another. 3) This can support the construction of deeper understanding if learners are able to abstract relevant features from representations to distinguish between shared features of a domain and properties of individual representations (Ainsworth, 2006). Thus, the efficacy of learning from multiple representations can be observed.

Seufert (2003) brings out that students must construct meaning from corresponding features of representations. This theory of coherence formation involves making connections both within and between representations, leading students to construct a coherent picture. This would of course require them to have adequate prior background knowledge, be able to work with multiple representations, and be able to recognize when two representations introduced a conceptual conflict. By focusing on both the "within" and "between" aspects of comparing representations, it would be possible to see where the conflict originated.

Dynamic Visualizations
There are many examples in the literature reporting on how students can successfully use dynamic molecular visualizations to connect with representations at other levels (Stieff & Wilensky, 2003; Ardac & Akaygun, 2004) Other studies showed that supporting creation

of atomic-level representations could foster connections among levels in chemistry (Wu, Krajcik & Soloway, 2001; Schank & Kozma, 2002). Learners could reconcile cognitive dissonance by paying attention to salient or key features when interacting with dynamic visualizations (Tasker & Dalton, 2008). Finally, the dynamic (Ainsworth & VanLabeke, 2004) and interactive (Moreno & Mayer, 2007) aspects of visualizations could be utilized to help students organize their ideas about chemical representations.

As for learning strategies, there is also documented evidence of the benefit of instructor techniques such as encouraging students to draw molecular-level representations (Davidowitz & Chittleborough 2009; Zhang & Linn, 2011). In addition, while no guarantee exists that visual representations side-by-side would help, highlighting the connection among various visual levels of representations seemed to have a positive effect (Ardac & Akaygun, 2004). Also, students did better when representations were placed together on a screen rather than isolated side by side (Bodemer, Ploetzner, Feuerlein & Spada 2004). However, external visualizations on paper or a screen are not always interpreted and assimilated faithfully into an internal visualization as a representation in the mind of a learner (Hegarty, 2004). In order for students to make sense of novel representations, they need visual similarities between the prior visual experience and the new representation (Wu, Krajcik & Soloway, 2001). The triplet relationship and the accessibility of technology open up new possibilities of conveying multiple representations, all with the potential to have a positive effect on student conceptual understanding and use of the "triplet relationship."

Transition

The following chapter proceeds to introduce the interview study that is motivated by this literature. Bruner advocated "creat[ing] a way of thinking...that is lithe and beautiful and immensely generative" (Bruner, 1969) when designing a curriculum. It is the hope that the strength of this study is not just in being immensely generative, but that it truly creates a new way of thinking about how to access what students know.

Chapter 3: Experimental Methodology

Introduction

The goal of this chapter is to describe the design, implementation, and analysis of an Interview Study created in order to answer the research questions posed in the earlier chapters. The questions posed:

a) What prior knowledge is activated when students are trying to make sense of a symbolic chemical representation describing equilibrium?
b) How has typical chemistry instruction impacted student ability to understand the common factors in representations of chemical equilibrium?
c) How can the triplet relationship help to illuminate and identify a mis-match between student conceptual understanding of symbolic chemical representations and macroscopic observable characteristics?
d) How can symbolic chemical representations be used to successfully link and connect macroscopic observations with atomic-level representations, thus promoting a richer understanding of the chemistry taking place at the molecular level?

This interview study was then designed with six steps by incorporating elements of qualitative methods research design and informed by prior work in chemistry education research. The interview study became an effective means to gather student ideas about chemical equilibrium, to see how they resolved conceptual difficulties, and how they meaningfully connected between multiple ways of representing equilibrium.

The interview focused on a simple expression commonly used in general chemistry:

$$HA + H_2O \rightleftharpoons A^- + H_3O^+$$

(hereafter referred to as the "given statement"). While strategically using multiple representations of the above expression, interview study prompted students to think aloud and generate possible and then plausible explanations for what this expression meant. Possible explanations are scientifically valid, whereas plausible explanations are not only valid, but also applicable to the investigation at hand. As demonstrated in this chapter, this "given equation" was manifested in a drawing exercise, experimental demonstration, equation-generating exercise, and computer simulation in an attempt to connect these multiple representations for students.

This study was conducted with chemistry learners with a view to taking advantage of the fact that learners construct meaning according to what they see as relevant. As documented in the literature as the *self-explanation effect* (Ainsworth & Loizou, 2003; Lombrozo, 2009), students benefit themselves and others while attempting to explain an idea (Rittle-Johnson, 2006; Roscoe & Chi, 2007, 2008). Self-explanations have been shown to be useful for student sense-making in physics and biology (Chi, Bassok, Lewis, Reimann & Glaser 1989; Chi, de Leeuw, Chiu & LaVancher, 1994). Results indicated that students were helped not only to learn, but also retained the information.

In this semi-structured interview, subjects were asked to provide observations to physical phenomena, as well as reason through the meaning of chemical symbols placed before them. An information-gathering style proposed by Wu et al. (2001) involved prompting students with a mix of conceptual questions that allowed for flexibility in continuing the interview. The interviewer was armed with a series of follow-up and probing questions designed to elicit students' elaborating on their ideas (Linenberger & Bretz, 2012).

Little work had been accomplished at the experimental intersection of all three representations of the triplet. While the previous chapter detailed a large number of authors who had focused on using two or even three representations in their research, few had incorporated an actual chemical experiment as the primary representation in their interview (Smith & Nakhleh, 2011), and none of those included a dynamic visualization as a complementary representation. Thus, the structure and design of this interview study alone is a novel contribution to the field of chemistry education research and will be examined more thoroughly in this chapter as well.

Study Participants

Demographics

All subjects were students at a large public research-oriented university located in the western United States. All students who had completed one of the introductory first-semester chemistry classes (Chem 1A or Chem 4A) were contacted by an email invitation. Subjects were given the option of receiving bonus points in their courses for completing a brief survey. Administered early in the semester, the goal of the survey was to learn about the types of students taking the first-year chemistry courses. Basic demographic information, as well as information about their chemistry backgrounds, was gathered about the students.

In total, 33 students participated in this study. The majority were between the ages of 18 and 20, 18 were female, and 15 were male, and 29 of these students were in their first year of university. The remaining students were either in their second or third year of post-secondary instruction. All of these students had completed at least one prior university chemistry course before the one in which they were currently enrolled, with some indicating that they had anywhere from 1-8 prior semesters of high school and college chemistry courses.

Regarding race/ethnicity, 25 of the subjects indicated that they identified ethnically as Asian, with all but two of those having an Asian/Pacific Islander background. The 7 remaining subjects identified ethnically as white, while 1 student was characterized as having a background from the Middle East. In addition, approximately 20 subjects indicated that English was their first language. The high number of Asian subjects is somewhat representative of the higher relative population of Asian students studying sciences who are enrolled at this university.

Previous Academic Performance
Variability for academic strength of the student was determined by using the prior semester general chemistry course grade. Based off of demographic survey data, all but 3 out of 33 interviewed students reported earning an A or a B in their first semester chemistry course. Over 2/3 of all interviewed students had completed an AP Chemistry course, with all but two having completed AP Chemistry or AP Biology before arriving to university (the ones who didn't completed secondary school outside of the United States). Thus, the argument can be made that, regardless of their track, all of these students had the capacity and adequate preparation to achieve above average in a college-level chemistry course.

Student Course Background
Out of over 1000 initial responses to the survey, 139 students in the Chem 1A sequence expressed willingness to be contacted for an interview, and 14 of these responded and participated in the interview. 95 students in the Chem 4A sequence expressed willingness to be contacted, while 17 of these completed the interview. In addition, there were two students who had just completed the first semester of the Chem 1A sequence. Thus, 31 of the students were enrolled in one of two chemistry tracks, Chem 1A/3A or Chem 4A/4B (the remaining two students were in the first semester of the Chem 1A/3A track). As seen in Table 1 below, students were enrolled in one of three categories of course sequences.

Table 1: Students Tracked by Course Sequence

Track Name	Typical Majors	Courses Completed	Students (n=)
Chem 1A/3A	Life Sciences, Engineering, Humanities	General Chemistry Organic Chemistry (1st semester)	17
Chem 4A/4B	Physical Sciences, Chemical Engineering	General Chemistry General Chemistry	14
Chem 1A/		General Chemistry	2

Students on the Chem 1A/3A track had first enrolled in one semester general chemistry (Chem 1A-General Chemistry), followed by the first semester (Chem 3A) of a two-semester organic chemistry sequence. The vast majority of these students (and all of the interviewees) had enrolled in high school chemistry, with a significant minority having had two years of high school chemistry. They were intended biology, engineering or other life-science majors who were explicitly NOT chemistry majors. The interviews occurred during the second semester, which meant that they were covering material representative of a first semester organic chemistry class.

Students on the Chem 4A/4B track were enrolled in a two-semester General Chemistry and Quantitative Analysis course. The majority had enrolled in two years of high school chemistry at the Honors and Advanced Placement levels. Most of these students had already committed to being chemistry or chemical engineering majors while applying to university, and as a result, entered this track with a greater perceived proclivity towards, and possible more coursework in, chemistry, math and physics. Since the interviews occurred during the spring semester, these students were finishing course content in a second semester of general chemistry.

Without intending to divide the interview population, some comparison of the two tracks was necessary when salient similarities and differences were brought out. The most obvious difference was that the Chem 1A/3A students spent only one semester studying general chemistry, before moving on to organic chemistry, while the Chem 4A/4B students had spent two entire semesters devoted to relevant general chemistry topics.

Less noticeable from the course descriptions (which seem to cover a large number of identical points) was the amount of scientific inquiry purposefully incorporated into the Chem 1A course by its instructor. On the other hand, the 4A/4B sequence placed a greater emphasis on mathematical manipulation. As an illustration, based on the author's own first-hand observation, students in the first week of class in the 1A course were examining how the type of bonding and functional groups present in different groups of biological molecules related to the properties of those molecules; those in the 4A/4B sequence were solving quantum wave equations.

Recruitment of Volunteers
In the initial survey, students were asked to respond to the following two statements: "I am willing to participate in an interview regarding my views on chemistry" and "I would be willing to evaluate a software designed to help future students understand concepts in chemistry." From a list of those who had given their consent to participate in a follow-up interview, students were solicited by email. While there was no monetary incentive to complete the survey, compensation of a $10 gift card to a local eatery was offered as a recruiting incentive and acknowledgement for participation in the interview study.

Timing of the Interview in Relation to Students' Chemistry Course Work
Interviews were carried out in a 2-week span immediately preceding final exams at the end of the spring semester. Thus, the majority of students were in the midst of preparing for final exams in chemistry courses at the time of the interviews. 24 of the 33 students were interviewed during the week immediately proceeding their taking the final exam scheduled for the following week. Interviews were conducted in one of two private interview rooms. They were scheduled to last no more than one hour, ranging from 42 to 55 minutes in duration.

A point-and-click industry-standard camera with video-recording capability was used to record audio and video. Cameras were placed in a position facing the students, so that the students' expression, voice and gestures could be optimally captured. The camera was also able to record any data being written on paper, as well as the students manipulating a laboratory setup in front of them. The final step of the interview involved viewing a representation on a computer screen, during which only the audio is available.

The interviewer followed a prescribed set of questions and prompts. The complete Interview Template is included as Appendix D. Due to the nature of the questions being asked and the nature of the information being sought, follow-up questions were generated that allowed for further probing of student thinking. In every step of the interview, the interviewer deliberately determined to have the student supply a conclusion or hypothesis. Due to the open-ended nature of the interview study, the interview required a student response before moving onto to the next step. This interview protocol was pilot tested and several modifications were made and incorporated into this study.

Pilot Research

Interview Design informed by Prior Studies
Based off of early pilot interviews, there was evidence that students who could successfully answer algorithmic examination questions about equilibrium struggled with depicting, explaining and communicating their thinking about those phenomena. Building off of the work of Zhang and Linn (2011), it was anticipated that drawing representations would be a useful instructive tool for further elucidating student thinking about equilibrium. Early interview work also revealed that second and third year college students who had advanced with aptitude through several traditional university chemistry courses still struggled with making connections across representations (Daubenmire, ACS 2011). This section describes some of the foundational work that informed the design of the interview study.

Student Conceptions from Two-Tiered Assessments
Preliminary research conducted using linked multiple choice assessments (two-tiered assessments (Treagust, 1988) provided great insight into how students were thinking about conceptual problems they were given. These items consisted of two linked multiple-choice questions or one multiple choice paired with one free response question. Questions were written in pairs in such a way that the second question asked the student to choose the rationale or explanation that best explained their answer to the first question. Students were also prompted to write out their reasoning or justification for their choice, using as many words as possible/necessary. This written data provided further insight into student conceptions, as they provided written rationale for their choices.

In the Fall of 2008, over 1300 samples of student work by first-year chemistry students in a semester-long Chem 1A class were collected (Scalise *et al*, ACS 2010). Of these, n=1007 gave the appropriate consent for their results to be included in the pilot study. Pre- and post-tests were designed from existing valid two-tiered assessment items (Tyson, Treagust, & Bucat, 1999; Mulford & Robinson, 2002; Yezierski & Birk, 2006), as well as other items that required students to generate drawings and explanations.

The collected data consisted of hand-written short answer problems that were administered individually during the first week as a pre-test and on the final exam as a post-test. These established a benchmark for measuring student learning gains. Scoring was accomplished by a group of approximately 40 graduate student instructors in chemistry, who had been involved in the instruction of the course material, and had spent time in a norming session to establish some inter-rater reliability.

An example free response question is listed in the Appendix B - "Lemonade" question, which was especially of interest because it asked students to correlate color with molecular behavior. This item became the precursor of the interview study, as many students struggled with determining how varying physical amounts of molecules and ions affected macroscopic properties. By collecting data from such a large sample of college students, it was possible to gather details about the varied types of conceptions students held at this level. Most importantly, these results strengthened the realization that even after completion of a general chemistry course, students did not easily associate symbolic representations with the macroscopic properties they were supposed to describe.

Early Interview Study
After sampling these larger groups with summative assessment items, more experienced chemistry majors were solicited for an in-depth conceptual interview. Through collaboration with a classroom instructor in the Fall of 2010, 31 third-year students majoring in chemistry and/or chemical engineering participated in a chemistry content knowledge survey. 35 questions were compiled from the Chemical Concept Inventory (CCI) – Mulford & Robinson (2002) and the Particulate Nature of Matter (ParNoMa) inventory - Yezierski (2006) on topics of stoichiometry, equilibrium, solubility. Perhaps, without surprise – considering the dedicated nature of these students, the average success rate was above 85%.

However, a more valuable aspect of these student interviews resulted from one-on-one think aloud interviews that included having students generate drawings to represent their thinking. Using variations of a see-saw as a bridging analogy to connect student thinking about equilibrium representations (Clement, 1993), it became more apparent that students were not actively thinking about the dynamic nature of equilibrium. An early outline for this dissertation's interview study was cultivated through these talk-aloud interviews (Daubenmire and Stacy, ACS 2011).

Early Dynamic Visualization Study
Volunteers from this same population participated in interviews surrounding their understanding of dynamic visualizations (PhET and Molecular Workbench). These have been useful to elucidate student thinking about representations. By showing students dynamic visualizations and asking them to draw molecular level views of these representations, it was possible to identify what aspects proved troublesome to them and what appeared meaningful (Zhang & Linn, 2011).

Postek's (2008) dissertation built off of Russell's work with the Simultaneous Multiple Visualization in Chemistry SMV: Chem software to investigate what students attended to when looking at external representations (Kozma & Russell, 1997). He allowed students to view four distinct visual representations and a voice-over of the same phenomena involving NO_2 dimerization. The four visual external representations consisted of a real time video of a chemical reaction (macroscopic level of understanding), a computer animation of the reaction (microscopic symbolic level), a graphical representation (macroscopic symbolic level), and a text representation (verbal text level) of a mathematical problem concerning limiting reagents. These were accompanied by auditory narration of the action that occurred during the representation. In interviews with 12 students, while the representations were found to be generally helpful in developing conceptual understanding, cognitive overload resulted if too many representations were engaged simultaneously.

During one pilot test, students were shown a depiction of equilibrium that involved a representation of bonds forming and bonds breaking (PhET, 2010; Molecular Workbench, 2010). A dynamic visualization of a reaction energy profile was displayed next to it, moving in sync with the bond formation. While both of these were common forms of representing an idea such as bonding, some of the junior chemistry majors professed that they had never seen these two representations juxtaposed in such a way and commented on their potential usefulness. This planted the seed that simultaneous but different representations of the same phenomenon might prove fruitful for investigation.

Based upon these preliminary interviews, the usefulness of student-generated representations and dynamic visualizations in strengthening the connections students make across multiple representations became more apparent. For example, surface features could be used to connect multiple representations to underlying principles. By allowing students to work with different representations whose features referred to the same chemical principles, these features could act as a bridge that allowed them to connect across multiple representations. Thus, knowledge or ideas gained from one representation could be tied to those gained from others, leading to a deeper understanding of the chemical phenomena.

Design and Overview of Interview Study

The interview study in this dissertation was purposefully designed to walk students through various representations of the same general given statement. Since the steps of the interview were focused on students' use and interpretations of different representations, it was important to delineate the results of these interviews according to these steps. An overview of the steps of the interview as well as a description of the performed tasks are displayed in Table 2.

Table 2 : Steps of Interview

Step	Representation	Assessment (Performance) Task
I.	SYMBOLIC: Interpreting the equation	Given equation talk-aloud
II.	ATOMIC: Drawing 4 Atomic-level views	Generating atomic-level drawings
III.	MACROSCOPIC: Dissolving a "Red" powder	Ranking by concentration and prediction of properties
IV.	SYMBOLIC BRIDGING OF ATOMIC TO MACRO: Ranking Concentrations of Species	Identifying and ranking species by concentration & revisiting atomic-level drawings

V.	SYMBOLIC BRIDGING OF MACRO TO ATOMIC: Adding strong acid to reform "Red"	Sorting samples by placing them over appropriate symbols
VI.	ATOMIC- MACRO: PhET visualization	Manipulating PhET visualization and generating equation to explain observations

In the remainder of this section is a step-by-step overview of the interview study. Each step is described in Tables 3-8. and includes these five characteristics: 1.)The STEP; 2.)the OBJECTIVES of each part of the interview are laid out; 3.) the ARTIFACTS section describes the actual tangible items that were placed in front of students, manipulated by students, or generated by students; 4.)the PROTOCOL section indicates the actual prompts or questions asked by the interviewer; 5.) the COMMENTS section, where follow-up questions or comments appear that are derived from pilot studies.

The first two steps of the interview were included primarily to establish a certain baseline of knowledge about the subject matter. Though students came from various chemistry backgrounds, it was assumed that they would be able to interpret the given statement at a foundational level of understanding. No students appeared to struggle with this most basic of symbolic representations in Step I.

Table 3: Characteristics of STEP I

STEP	SYMBOLIC: Interpreting the equation
OBJECTIVES	-Establish a baseline of student's conceptual understanding of acid/base chemistry through the use of basic terminology
ARTIFACTS	$HA + H_2O \rightleftharpoons A^- + H_3O^+$ was written as the "given statement" at the top of an otherwise blank sheet of paper.
PROTOCOL PROMPTS	"This is a statement that you've seen projected on a screen, on a blackboard, on your computer or even in a textbook. What does this statement mean to you? -What does this symbol (equilibrium) mean? -What physical properties, such as color, temperature or phases would you expect? -What additional information do you need from me to make sense of this?"
COMMENTS	The interviewer purposely stayed away from follow-up questions that prompted students to perform mathematical calculations or to think about concrete numerical values. Though a quantitative discussion of K_a was accessible, it was not necessarily fruitful, and thus was not encouraged.

The first step of "interpreting the equation" was designed to provide students an opportunity to express their ideas. Most students were very comfortable with this step of eliciting ideas in the interview.

Table 4: Characteristics of STEP II

STEP	ATOMIC: Drawing 4 Atomic-level views
OBJECTIVES	-Elicit thinking on the atomic level -Attempt to find out what students know through asking them to explain their drawings.
ARTIFACTS	Blank sheet of paper was divided into 4 quadrants and pre-numbered so that the drawings could be quickly referenced later.
PROTOCOL PROMPTS	"Now imagine you can zoom in on this statement so that you could see individual atoms. Draw for me what this statement looks like in the following 4 scenarios. "Draw before" (or, the moment when they're combined) "Draw slightly before" "Draw slightly after" "Draw what it looks like after a long period of time has passed."
COMMENTS	-Elucidate what "before the reaction" means in the students conception -"After the reaction" has occurred Even when a student drew "normative" drawings, it was important to ask them what their understanding was. Once the fourth drawing was produced, students were asked to look at the symbolic representation once again and rank the amount of each species present in that drawing.

The goal of Step II was to illuminate what types of representations students associated with the given equation. Students were asked to generate 4 drawings of atomic-level representations that corresponded with how they thought about the given statement. Using 4 quadrants of a sub-divided sheet of paper, students were asked to draw what they thought the given statement looked like over time, at 4 different time points: 1) before, 2) slightly before, 3) slightly after, and then 4) after a long period of time has passed.

After completion of the 4^{th} diagram, they were then asked to rank the relative concentrations of each species once they had reached a future point in time (corresponding to equilibrium). The goal of this step was to reveal the type of thinking that students held about the symbolic equation, and to allow them to interact with the dynamic nature of the equilibrium statement. In a simpler sense, students were being asked to generate what a simulation of the given equation would look like over a period of time.

Table 5: Characteristics of STEP III

STEP	MACROSCOPIC: Dissolving a "red" powder
OBJECTIVES	-Identify physical properties of a solid unknown -Relate solid unknown to HA in SYMBOLIC representation

ARTIFACTS	1.) Students are shown a sample of methyl orange (red-orange solid) 2.) A small grain is put into 50 mL water in a 150 mL beaker. 3.) Add water to bring volume of solution to 120 mL.
PROTOCOL PROMPTS	"Here is a vial. The contents of this vial can be described as HA, a weak acid. 1.) Describe what you expect to see. 2.) Predict what will happen when you put one grain of this in 50 mL water. What color? What phases? What do you expect to see in solution? 3) Put small grain into 50 mL water and stir. 4.) Observe the solution – what do you notice? 5.) Predict what will happen when we further dilute this solution by adding 70 mL of water. What color would you expect? What do you expect to see in solution?
COMMENTS	Because the initial solution of 50 mL was a dark shade of yellow and the 120 mL solution was light yellow, many interviewed students believed this was due to dilution. If students predicted a color, such as red, orange or clear, the interviewer prompted them to explain their reasoning or rationale.

Step III involved adding a small amount of red-orange solid HA to water. It was anticipated that the big conceptual difficulty in this process involved explaining why the color change went from a red-orange to a yellow color as more water was added, which was not just due to dilution. This was a point where something was not just dissolving anymore, like fruit punch powder would dissolve, but that actually both dissociation (an invisible process) and dissolving (a visible process) were taking place. The conceptual difficulties involved in this process are explored in Chapter 4.

Students were also asked to make predictions about what they would expect to see at various stages of the interview, including anticipating the yellow color of the initial undiluted HA solution, and attempting to explain the color of a dilute HA solution. This will be examined in detail in Chapter 5.

Table 6: Characteristics of STEP IV

STEP	SYMBOLIC BRIDGING OF ATOMIC TO MACRO: Ranking concentrations of species
OBJECTIVES	What occurs on the ATOMIC level to explain the colors we saw? Based on what you have in your beaker, how does the statement describe what you see?
ARTIFACTS	Students copies down the initial statement onto the top of paper #2.
PROTOCOL PROMPTS	"1.) Describe what you see in the flask. 2.) Rank the species in terms of the greatest amount of each species present. 3.) Under each species, list its contribution to color. What color

	does each species contribute and why? Draw for me what this looks like if you can see the individual atoms."
COMMENTS	Color change in the previous solution is expected to be challenging for pilot students to understand, based off of pilot work.

During Step IV, students were asked to rank the relative amounts of each species according to their understanding of concentrations. Through using a ranking system, where "1" was the most prevalent, and "4" was the least prevalent, students were also asked to describe how much of each species was present, as well as the corresponding colors those species were expected to produce. The goal of this step was to allow students to form referential linkages between the atomic-level and macroscopic representations by discussing the connections (Wu, 2003).

Table 7: Characteristics of STEP V

STEP	SYMBOLIC BRIDGING OF MACRO TO ATOMIC: Adding strong acid to reform "red"
OBJECTIVES	-Application of Le Chatelier's Principle to expose student thinking about equilibrium and the reversibility of a reaction -Placing samples over appropriate symbols
ARTIFACTS	Add concentrated H^+ in the form of one pipette drop of 0.6 M HCl Vial of Red HA powder, a beaker of yellow A^- liquid, clear H^+ liquid, clear H_2O liquid, and a beaker of red HA liquid
PROTOCOL PROMPTS	"Now, we will add a source of H^+. The only species contributed to our statement is H^+ (any other species present do not react.) I will add less than 1 mL of H^+. 1.) What is your prediction concerning what you will see? What else could you see? What colors or phases could you expect? 2.) Does this match your expectations or is it surprising? Draw: What is happening on the MACRO level? What is happening on the ATOMIC level? Generate a(n) equation(s) to describe the process you just witnessed. Are there more than one taking place?"
COMMENTS	In this STEP, students may just refer to the drawings they produced in Step II. Possible Issues to probe with students: Aqueous - Why draw it that way? Dynamic - Why would it shift?

	Endpoint - Do they stay together/react forever? Reversibility – Is there any point of completion? LeChatelier's Principle - What does that mean on the ATOMIC level? Dynamic view is not relevant when equilibrium is first established. Compensate for addition of H^+, so there are more A^- colliding with H^+ Appearance - What color is produced?

Step V involved adding a strong acid as a source of H_3O^+. This would be so that the equilibrium reaction would reverse to involve re-forming starting materials. According to Le Chatelier's Principle, students would be able to understand that a stress on the system would merit a corresponding shift in the equilibrium.

This final experimental step involved putting several ideas together by manipulating each of the beakers of substances in the interview. Students were given the following equation, and were asked to place each of five species on top of the symbols that were written out in front of them:

$$HA + H_2O \rightleftharpoons A^- + H_3O^+$$

This was also a point in the interview where it was anticipated that conceptual difficulty would be resolved due to clearer experimental evidence.

Table 8: Characteristics of STEP VI

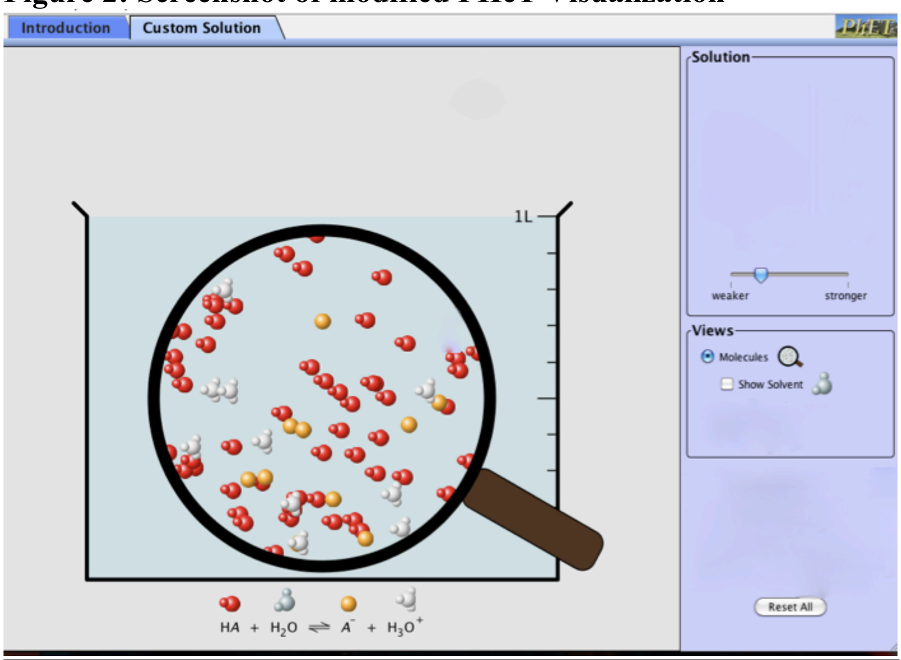
STEP	ATOMIC- MACRO: PhET visualization
OBJECTIVES	-Use a learning technology to strengthen the link between color and the ATOMIC level representation
ARTIFACTS	PhET Acid-Base Solutions module was customized so that the HA molecules appeared the same hue as the actual unknown solid. The shading of the A^- particle was adjusted to more accurately reflect the color of the fully diluted A^- solution. -The sliders in the visualization allowed the students to increase or decrease the relative amounts of HA or A- particles present.
PROTOCOL PROMPTS	"Notice the statement we have been working with and the statement on the visual are the same. Describe to me what you see when you move the slider on the visualization." 1.) Move the slider to show me where the solution resulting from HA powder and H_2O is. Why this point? 2.) Move the slider to show me where the solution resulting from adding H^+ is. Why this point? Why not further to the left? Follow-Up Questions: -Is there anything missing from this visual? Where does the visual deviate from the given equation?

	-Do you want to see the water? Is it helpful or confusing? Do you want to keep the water? -What does the visual connect for you?
COMMENTS	A desirable outcome of this step of the interview was to have students revisit the SYMBOLIC representation and have them, starting with the solid HA, generate an equation or equations that would convey what was experimentally performed before them.

In this final step, students were asked to look at a computer simulation using the PhET software in order to describe how the given equation represented actual conditions in the experiment. The strong potential existed for a connection to be made between the colors of the simulation, and the given equation reproduced below the simulation.

PhET simulation
A simulation called "Acid-Base Solutions" was utilized from the PhET Interactive Simulations website (2013). PhET is a website containing Physics visualization programs. A slight customization of the program achieved through programming assistance allowed for the involved changing of the default colors displayed in the visualization. The colors were selected to match the endpoints of the demonstration as seen in Figure 2:

Figure 2: Screenshot of modified PHeT Visualization



Three Levels of Data Analysis
There were 3 lenses of analysis proposed in this dissertation (Metz, 2004). The first two levels focused on resolving conflict between different types of representations. As detailed in Chapter 4, the first lens examined how students responded to conceptual difficulty or dissonance between a macroscopic and a symbolic representation. This was accomplished by exploring the conflict between a dissolution model and dissociation

model of the dissolving process. The analysis was conducted on student's written work and substantiated in the spoken component of their interviews. A final written item and follow-up probing questions allowed for insight into how students were resolving the conflicts between these two models.

The second lens (Chapter 5) focused on students' understanding of how a macroscopic representation correlates to a molecular-level representation as translated through a symbolic representation. More specifically, students needed to use the overall color of a solution to resolve conceptual difficulties in determining the relative amounts of actual molecular-level particles. Thus, it was anticipated that students' understanding of Le Chatelier's Principle was incorporated into their explanations for why the reaction results in a color change. Ultimately, the goal of this level of analysis was to reveal that students were able to examine and explain the color of a species based on just the color of the original particles.

The third lens (Chapter 6) examined four representative pathways that students might undertake in the course of examining all of these multiple representations. In this chapter, students were categorized into four groups depending on how they verbalized conjectures.

Coding of Subjects

For the purpose of coding, all subjects were assigned a non-identifying code, which begin with "4B" followed by a number. All student-generated written artifacts were collected and scanned. The content of the video interviews was transcribed. Poor audio quality was documented with six of the thirty-three interviews, and these were mostly set aside during the course of the analysis. Table 9 documents some of the steps required to prepare the transcripts for analysis.

Table 9: Preparation of data for analysis

1.)	Data Transcribed by three transcribers
2.)	Numbering of line items was inserted into transcripts
3.)	Identify line items and time stamps to determine location of Steps
4.)	Interview text subdivided into Steps
5.)	Written artifacts scanned into digital format
6.)	Gestures and written artifacts inserted into transcripts

During transcription, special attention was paid to indicate when students gestured towards the experimental setup or their written work. A final step in preparation for analysis involved intercalating digital images of the written artifacts with the written transcripts. This was accomplished through re-watching of the video footage, and noting the target of gestures as students were being interviewed. Rather than merely writing out the word "THIS" or "THERE," a picture of the object in question was also included for clarity. An undergraduate research assistant was involved in intercalating the written and audio data for analysis. The primary author was involved in coding all transcripts.

As the interview study was conducted as a semi-structured interview, it was anticipated that the interview would proceed with some variation. However, the prompts at the beginning of each Step provided necessary signposts for evaluating student progress through the interview. Thus, the data could be evaluated in a uniform manner.

Summary

This chapter began with a normative acid-base equilibrium statement that typical college students studying chemistry would be expected to understand and interpret. Through the six different Steps of the interview, the goal was to see where conceptual difficulties arose for students, and to determine how students resolved conflict by connecting across multiple representations. This chapter detailed an interview study where learners expressed their ideas as they faced moments of conceptual difficulty. Later chapters will analyze what those ideas were, what the difficulties were, and how the students sought to resolve them.

Chapter 4: Resolving Conflict between Macroscopic and Symbolic Representations - Viewed through the Lens of Dissolution and Dissociation Models

The Conflict

The purpose of this chapter is to focus on a particular conceptual difficulty that arose when a student's interpretation of an observed chemical phenomenon conflicted with the symbolic representations of that same phenomenon. A particular equilibrium scenario introduced in Step IV could be understood as either a dilution taking place or a new substance being formed. Using the lens of a symbolic representation of a phase change, it became possible to gain further insight into how students interpreted the given equation. In addition, it was possible to use the interview study as an assessment to diagnose what type of conceptual model a student possessed.

As evidenced in the literature in the previous chapter, students have had difficulty in connecting visible macroscopic evidence with the appropriate molecular-level representation. The underlying processes of dissolving and dissociating provide an excellent opportunity to explore student capacity to work between representations, since the former process involved a visible and the latter, an invisible component. An additional process required of students involved linking the symbolic representation with the observable evidence presented in this interview- in this case, the solid HA and subsequent dilution by addition of water. These connections were not always straightforward, and as will be evidenced by the analysis of student work in this chapter, an incorrect link made by students could create even further difficulty in understanding the phenomena.

$$HA + H_2O \rightleftharpoons A^- + H_3O^+$$

A simple equilibrium expression as shown above could be interpreted in many different ways, depending on the context in which it is placed and what symbols are attended to by the observer. For example, looking only at the letters would place emphasis on the identities of the species present. The double-headed arrow would elicit meaning as to the reversible nature of the reaction or the fact that the reaction was at equilibrium. Additional characteristics such as the state of matter, while also certainly important, were not explicitly described in this statement. Finally, it was reasonable to expect that part of the challenge of the interview was identifying what submicroscopic characteristics were being referenced by a certain chemical symbol.

Schultz (1997) reiterated that learning chemistry is like learning a language, and pointed out that multiple terms in chemistry do not mean the same in everyday English. In addition, he addressed the difficulties that the chemistry education community as a whole has had in agreeing to appropriate uses of the terms 'dissociation' and 'ionization.' If the experts are having trouble agreeing, then surely novice students will face difficulties in distinguishing between the two. The goal of this particular analysis was not to debate the merits of teaching these distinctions in typical classrooms, but to illuminate the types of thinking students were engaging in when faced with the differences.

Defining Dissolve vs. Dissociate
For the purposes of clarification, dissolving is described as a physical change involving the mixing of a solid solute into a liquid solvent. During this interview, since the solid used was a red powder, it was possible to observe the disappearance of the powder into water as evidence of dissolving. Dissolving is the physical process of particles of a solid interacting with molecules of a liquid in order to disperse the solid throughout the liquid medium. Dissociating is an equilibrium process of a substance breaking up into individual ions in the presence of a solute, resulting in the formation of a solution, where the solute ions are dispersed among the solvent molecules.

For example, when the two terms 'dissolve' and 'dissociate' are presented separately as definitions, students attempt to define the former as a physical process and the latter as a chemical process. In addition, they can use these definitions for appropriate physical examples. However, when shown evidence in an experimental setting, the distinctions between the two became less clear. Students would switch back and forth between their usage of the terms, and even use the terms interchangeably.

Salt vs. Sugar
An illustration of the distinction at the atomic level between the "dissolution model" and the "dissociation model" is a description of what happens when sugar and salt are each put into water. Upon contact with water, sugar remains intact in the molecular form and only separates into smaller sugar molecule clusters. A student brings up this way of thinking, (but then mistakes the word "dissolve" for " dissociate").

Student 4B21, Line 218

> P: What explanation do you have about the powder? What's going on in there?
> S: The water is not… I am going to use the sugar example, you have a bunch of powder, but the water is not enough to dissolve it, it's just enough to break it into smaller pieces. That's still visible, and that's why you see the solid stranded in clumps.

On the other hand, salt breaks into individual ions with their own distinct properties when it comes into contact with water. Unlike this illustration with two crystalline household substances, the example with HA in the interview study is unique because it undergoes BOTH processes. HA dissolves as a molecule and it dissociates into ions.

As it turns out, due to its chemical structure, methyl orange (HA) is a substance that can be categorized as a weak acid. A weak acid, as is often taught in introductory chemistry courses, is a substance that dissociates into its conjugate base and H_3O^+ but where the ions also recombine at an appreciable rate in the reverse reaction. Thus, it would exist in water both as HA, and as A^-, with the relative amounts depending on the identity of the acid and the solution pH. Using the "salt" and "sugar" analogy once again, methyl orange exists in solution as a little bit of salt, and a whole lot of sugar.

Methods

Initiating the Phenomena – Step IV
During this step of the interview, HA powder was placed into water, causing two distinct processes to occur. First, the unknown HA solid initially began to dissolve into the water, resulting in tiny wisps of red color. These little wisps often appeared to be tails accompanying or attached to red clumps of solid. Second, as the substance dispersed throughout the solution, even without stirring, the surrounding transparent water began to take on a distinct yellow color.

This arose from the fact that two distinct, but related processes were occurring simultaneously upon addition of HA. The first process resulting in a red color arose from the dissolution, or dissolving, of HA solid into individual HA molecules. This process can be described by the following chemical equation:

$$HA\ (s) \rightleftharpoons HA\ (aq)$$

The second process involved the breaking up of solvated HA molecules into individual ions. This process of dissociation, or dissociating, of the HA into its ions resulted in an overall yellow color. This process can be described by the chemical equation given below:

$$HA\ (aq) \rightleftharpoons H^+\ (aq) + A^-\ (aq)$$

The overall process can be described as:

$$HA\ (s) \rightarrow HA\ (aq) \rightleftharpoons H^+\ (aq) + A^-\ (aq)$$

Students Ranking of Concentrations
An additional step in establishing the baseline of student prior knowledge was determining what they believed to be the relative amounts of each of the species present once HA was added to water. In asking them to rank the concentrations of each species once a long period of time had passed, it was possible to determine which species they believed to be most prevalent. As a result, this could be used as a gauge for determining whether there was a match in their understanding of expected color (macroscopic representation) versus number of particles (molecular-level representation).

Data were collected by asking students to write down a numerical ranking corresponding to the relative amounts of each species (HA (s), HA (aq), H_3O^+ (aq), and A^- (aq)), with "1" being the highest and "4" being the lowest. Species that had the same amount were ranked with the same number. Out of 33 students samples, 29 responded with rankings that were clear enough to analyze in terms of relative amounts of HA or A^-.

Thirteen indicated that the concentration of HA would be greater than the concentration of A^-, and sixteen indicated that the concentration of A^- would be greater than the concentration of HA. While these data are not significant, in future work it can be linked against students' descriptions of colors to see if there was any significant correlation.

Models of Interpretation

Through analysis of student comments on these two phenomena, it became possible to develop a more comprehensive idea of how they were integrating their chemical ideas. Student thinking manifested features of one of two ways to think about their observations: 1) a Dissolution Model or 2) a Dissociation Model[2] . A student's observation of colors could be used to reconcile the debate between which type or types of models he or she preferred. (An in-depth exploration of their understanding of color is undertaken in the next chapter.)

The analysis was based upon two distinct timepoints where a conceptual difficulty was created during the interview study. The first timepoint (Step IV) occurred when the solid red HA was added to water in light of the Given Equation to produce a yellow liquid. The second timepoint (Step V) occurred later in the interview when an acid (H^+) was added to the resulting yellow liquid to result in a red liquid. At both of these timepoints, it was possible for a student to overlook or ignore the Given equation. Their resulting attempt to explain the phenomena would reveal what type of model they possessed. Outside of the context of the supplied information, they would favor a dissolution model whereas those informed by the Given equation would rationalize the dissociation model.

1) Dissolution Model (Dissolving)

Table 10 at the end of this section indicates normative ideas that students would be predicted to have when possessing a dissolution model. While not made explicit in writing, it was communicated to students that HA was a red solid, and through their deduction, they could recognize that it would dissolve in water. Thus, subjects might expect that a red solid dissolved in a clear liquid would result in a red liquid. This model seemed to make sense as long as the solid HA was not placed into a solution. However, once in contact with water, a yellow liquid was formed. This model alone could not explain why this occurred when HA was dissolved in water.

Student difficulty with this idea stemmed from their intuitive belief that a red solid dissolved in a clear liquid would result in a red liquid. However, the macroscopic evidence proved challenging to their reasoning. The properties of HA molecules would be the same as for the solid HA sample, including the presence of the red color (Ben Zvi et al., 1988). However, in their every-day experience with solutions, it was possible for a solution to be a slightly different shade of color depending on how much water was added. Most students commented initially that the expected prediction for the dissolution of a red powder would be a red liquid. Since most students used this observation at timepoint 1, before the addition of water, they were classified as subscribing to a "dissolution model."

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[2] To be fair, the Dissociation Model is technically the Dissociation Model preceded by the Dissolution Model.

2) Dissociation Model

Table 10 below indicates normative ideas that students would be predicted to have when possessing a dissociation model. According to this model, students could depend on the fact that HA would dissociate into an A- anion. They were willing to acknowledge that the A- ion could indeed be a different color from HA.

This model seemed more valid to some of the students, because it allowed them to consider the product side of the chemical equation. It made sense to them that an acid in the presence of water would produce H_3O^+ and A^-. Thus, it was less surprising to them that there would potentially be another color present in the beaker, because they were willing to consider the other available species.

It must also be pointed out that the central equation supplied to students at the beginning of the interview is an abbreviated description of a substance undergoing dissociation. Indeed, seeing the following equation was equivalent to "priming" students to think about dissociation.

$$HA + H_2O \rightleftharpoons H^+ + A^-$$

Thus, it is possible that the "dissociation model" would be favored for any discussion of the experiment, since students were also seeing an equation that they were familiar with in the context of dissociation.

However, one large conflict between the experiment as performed and student thinking resulted from their need to overlook the fact that the equation written in front of them did not contain adequate information for them to determine whether HA represented a red solid substance or a dissolved red aqueous substance (but not yet dissociated) in a clear liquid.

Here, the data based off of students' interviews revealed that a significant number of students observed a chunk of solid red HA that was present when mixed with water. Whether described as red "wisps," "flecks," or even as "tails," it was clear to these students that in addition to formation of a yellow liquid, a red solid was present. By the time all the red HA solid had "disappeared," it had been converted to yellow A^-, which is ultimately what the yellow color can be attributed to. The production of this species, called the "A^- ion," is through a process called dissociation. During the course of interviews, students who referred to this process were coded as discussing the "dissociation model."

Analysis of Data - Summary of Conceptual Difficulties

Summary of Expected Conceptions

In this analysis section of the study, there was sufficient written evidence from 33 students. Student ideas were analyzed for insight into how they were using the symbolic representation in light of the conceptual models. From the two models, ideas were compiled in order to generate Table 10 below and were organized to correlate student observations with the actual chemistry taking place at the molecular level.

Table 10. Expected conceptions predicted by models

Step	Process	Dissolution Model	Dissociation Model	Normative Model
Step I	Equation	Written equation doesn't match model	Written equation matches model	A need to revise written equation
Step II	Drawing	"Sugar" – aqueous HA	A "salt" (ionic compound) forms - H^+ and A^-	A weak acid acts as "sugar" and "salt"
Step III	Solid HA	A red solid	A red solid	A red solid
Step IVa	HA slightly dissolved	A red liquid	A clear liquid that is red or possibly another color	A red liquid becomes a yellow liquid
Step IVb	HA greatly dissolved	Dilution to lighter red liquid	A disappearance of HA, and a liquid that is possibly a lighter shade of Step IVa	A lighter shade of yellow
Step V	H+ added	Solid possibly reforms with no color change	A solid reforms with a possible color change in the liquid	A color change to red liquid
Step VI	Visualization	Intact HA expected to be present	H^+ and A^- ions to be present	A color change supported by presence of more HA particles.

Evidence of Conflict in Student Interviews

Student 4B2 was a typical student who could talk about a wide range of ideas when the interview began. This student brought out terms when initially shown the symbolic equation: "dissociation," "equilibrium," "acid," and "base" immediately explaining his understanding in the context of these words. Unprompted, he specifically requested from the interviewer to find out more about K_a of the reaction, in order to decide whether the left or the right side of the reaction was favored. This student correctly believed that knowing the pKa of the acid in question would provide insight into the behavior of the system. However, as the interview required him to discuss dissolving and dissociating, it became clear that he did not make a clear distinction between the two, and often used them interchangeably

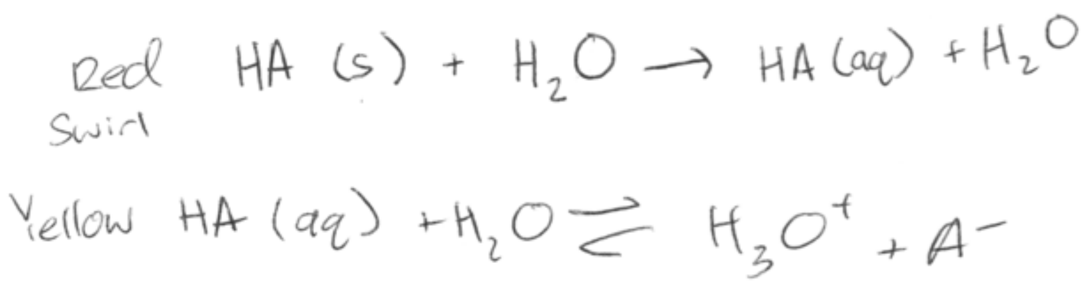
Using the lens of these two models was effective for evaluating students' use (or mis-use) of representations. Could a student generate a statement, either verbal or written, that conveyed an understanding that both a dissolution and dissociation model were taking place? Success in this aspect of the interview was measured using a simple metric. Did the student acknowledge that a macroscopic step had occurred described by the following chemical equation: HA(s) → HA (aq). Ultimately 18 students out 30 were able to generate some form of the above modified equation after Timepoint 2 to appropriately indicate the processes taking place. While some of the remaining students quite possibly could have explained the phenomena, they struggled with generating a symbolic representation that could accomplish this.

Below is a representative statement by a student capturing the essence of the shift from a single-step dissolving process to a two-step dissolving process. In the transcript, the student points out not only that there should be unreacted solid HA in the beaker, but that it would also exist as aqueous HA. In Figure 2, generated at the end of the interview, the student is quite clear to indicate the two processes taking place that would result in the two colors that were seen.

Student 4B9 lines 380-384

> P: … what was that swirling red we saw? We didn't really address that in the beginning.
> S: My guess is that that's just some of the solid acid in water- that has not really reacted, because I guess that would make sense.
> P: … is there an equation to describe that?
> S: um… I guess, there's both present, so I guess the more accurate thing is that there's HA (aq) and HA (s).

Figure 3. Depiction by Student 4B9 at the end of interview



As the data were being reviewed, it was possible to see five distinct types of conceptual difficulties that students were having. It is purported that depending on whether students were able to resolve these difficulties or not was dependent on the models that they used. Since more robust uncovering of facets was not the goal, these interview results teased out subtle levels of distinction in student thinking, as described below.

A.) The first difficulty is that when students encountered dissolution, they had not been considering dissolution as a process that was relevant to this equation. Though they may have observed it, most didn't pursue this observation because the given equation did not prime them to consider dissolution.

B.) Since there was no mention of dissolving in the written equation, students did not address it. It is often the case in chemistry instruction that the phases of matter are not included in a chemical equation, thus creating unintended confusion for students who are trying to make sense of the information.

C.) Some students failed to observe or mention that they had observed a red solid floating in the solution. This observation was crucial to understanding and explaining that two different processes were taking place simultaneously. More importantly, the presence of the red solid was proof that the solid HA was gradually and finely breaking into smaller HA units (individual molecules).

D.) As opposed to the previous idea, some students went so far as to comment on the red solid floating around. However, after making the observation, they failed to follow up to try to explain the significance of this observation.

E.) Some students considered these the same process. This was evidenced by their almost indiscriminately interchangeable usage of dissolve and dissociate.

These student conceptual difficulties that arose in the interview study were compiled into the table below.

Table 11. Possible Student Conceptual Difficulties

A.)	They were not actively acknowledging that dissolution occurs.
B.)	They were not considering dissolution as a process relevant to their observations.
C.)	They were overlooking evidence that didn't support dissociation.
D.)	They were misinterpreting evidence that didn't support dissociation.
E.)	They were considering dissolution and dissociation as the same process (or failing to point out that dissolution and dissociation were distinct processes).

In the course of the interview, 17 out of 33 students were initially not able to reach a conclusion that incorporated these two steps. In other words, without assistance or prompting, they were not able to generate a written statement that conveyed this understanding. Thus, a further analysis was needed to understand why over 50% of the interviewed students struggled to reach a somewhat elementary conclusion from a chemistry perspective.

Results & Discussion: Resolving the Conflict – Priming for Dissociation

Why was there difficulty for students in understanding dissociation? Students have been trained to associate chemical ideas and concepts to chemical symbols. Thus, certain symbols evoke certain ideas or concepts. When there was not an explicit link being made, it became challenging to connect these symbols back to a macroscopic observation, or to an even more meaningful molecular-level representation.

Based off of the Given equation at Timepoint 1, students might have thought that they were expected to talk about dissociation. They may even have been primed to think about the dissociation of an acid into hydronium ion and its conjugate base. However, from the macroscopic perspective, students were presented with a red powdery solid. When that red solid was dissolved in a liquid, the expected and intuitive result was a red solution, like watching Kool-Aid powder dissolve to make a red drink.

Origin of Conflict
Thus, the conflict originated from a mis-match between what the symbolic representation was presenting (expect red HA solution), and what was observed as the macroscopic representation (a yellow solution). By revisiting the compartmentalized manner in which students are typically taught chemistry, it is possible to see that students needed a fair number of clues or input in order to correctly connect between these representations.

If there is no prior knowledge in a particular field, students may able to assimilate new information as "new." However, more frequently, previous ways of thinking can be useful for students to organize new information into their existing understanding. Teichert and Stacy (2002) found that students who were taught in a context that integrated their initial conceptions about bond breaking had a deeper conceptual understanding. However, when this information is in a context where it apparently contradicts their existing understanding, it is apparent that even a familiar representation could unintentionally prepare students to think in a way that contradicted the representation's intent. This creates a conflict between what is represented and what is observed.

Given the fact that students had been supplied with a very standard chemical equation, it was surprising that they were not able to translate the equation. While it was possible that at a basic level, students did not know the fact that a weak acid did not dissociate 100%, this was not probable, considering the level of training that these students had completed. Rather, it seemed more likely that they were ignoring clues in the observable experimental data that could have readily clarified what they were examining, because these data did not match with their existing ideas. Rather than referencing the normative scientific explanation that was described in the Given equation, they ignored it and struggled to make sense of the observations intuitively.

During the course of the interview, prior knowledge was exposed and challenged
It became clear through this part of the interview that students were being "cued" or "primed" through the use of chemical symbols. A symbolic representation written without the accompanying states of matter presented a potential nightmare for students, not knowing in which way it could or should be interpreted. Because the states of matter were not included initially, it was possible that students were thus not troubled by inconsistencies. Rather than noticing that the given equation did not match up with the data they were examining, they were content to disregard this. Thus, they were not clear as to what they should have been focusing on when attempting to interpret the symbolic representation.

This part of the interview proved universally challenging to most of the students. Because of the experimental design, students needed to examine multiple pieces of evidence over a period of time in order to develop a conceptual understanding of the macroscopic evidence. Students were cued by symbolic expressions, and some supplied facts or statements that were incongruent with or even contradicted the physical evidence in front of them. For example, whether they are given HA as solid (s) or aqueous (aq) altered how they discussed the model in front of them.

Since they were being cued in a certain manner to believe that dissociation was taking place, they had to rely upon their conceptual understanding to rationalize additional evidence that they had observed. This strengthened the principle that students may have been focusing on the wrong information in a chemical representation because they interpreted the chemical symbols in an irrelevant, or even inappropriate manner. (For example, Student 4B02 chose to describe a color change as being due to "ligand-theory." While this had no apparent relevance to the visible data, this became an idea that grew in this student's consciousness as the interview progressed.)

Making Conjectures

Critical to the students developing their understanding of the chemical phenomena was their usage of conjectures to help them sort out the experimental data. While the pathways are explored in more depth in Chapter 6, it is important to notice that the conjectures presented at this point were preliminary statements made by students attempting to coincide or rationalize the experimental data with the symbolic representations.

When facing some surprising results, one group of students answered along the lines of "I didn't expect that" or "I wonder why that happened," which created opportunities for the students to ask questions of themselves, to think metacognitively and to reflect on their observations. One group of students found something surprising and asked themselves, "Why?" A second group of students asked whether there was anything else added to the solution, as if they had not paid attention to some information earlier. A third group of students essentially pointed out that this was a surprising result, but did not seek for a further explanation.

Table 12. Examples of metacognitive behavior

Level Group	Response
1	"I didn't expect that. " I wonder why?"
2	"Was anything else added?"
3	"That was surprising."

Teacher/Educator's Role – A Desirable Conceptual Difficulty

Priming Students

Thus it can be seen that the structure of the interview created a moment of conceptual difficulty that forced students to resolve a dilemma between observable experimental data and a symbolic equation. Because of the mismatch, students needed to choose and defend a model to explain what they observed. Because the equation seemed to "prime" for a dissociation model, it was hoped that students would be more likely to notice and discuss features of the relevant model, rather than incorporating all the physical evidence or processes happening in front of their eyes. Thus, the context in which the student viewed the evidence was crucial.

Students' Responses

To illustrate: as students noticed the red solid dissolving into a red liquid tail before "disappearing into the yellow solution," they had to make sense of a piece of evidence that was not explicitly addressed by any symbolic equations. Students needed help to realize from the evidence in front of them that BOTH dissolution and dissociation were taking place as visible processes in front of them, even though both were not being described by the equation before them.

Thus, the interview could be viewed not only as an intervention or instructional activity but also as an assessment to measure how effectively students distinguish between competing chemical models. As indicated in the previous chapter, these students had adequate prior subject content knowledge to understand the chemical symbols as written. Yet there was sufficient evidence to show that students were not able to translate or connect between these representations. Thus, it is less clearly known whether students were misunderstanding or merely misinterpreting the focus of those symbols.

As will be brought out further in the remainder of this dissertation, it appears that the instruction that accompanied the interview helped students in translating from observable data to molecular-level representations. (However, it's important to note that in terms of content knowledge, the given equation had significantly more meaning for the interviewer as an expert than for the student). By scaffolding or tutoring these students, it can be argued that this type of instructional interview can be used to help students resolve conflict between two models.

Conclusion: How is Dissolving/Dissociating a Lens into how students use evidence to inform their models about equilibrium?

If students can interpret what is happening at the molecular level when they observe a chemical process taking place, they can develop a richer understanding that goes beyond merely memorizing chemical formulas. Surely an ambitious goal for instruction is that every student is helped to understand each concept presented to them. Yet, through the use of a simple chemical formula, a student was able to achieve much in terms of discussing chemical representations. On the other hand, if they failed to recognize that the chemical formula bridges for connecting two types of representations, look at how overwhelming chemistry could be!

In this case, if a student was unsure in which direction the symbolic equation was cuing them, their thinking could lead them in a direction completely opposite of the instructor's intentions. However, properly wielded, the symbolic representation could lead to a much richer understanding of chemistry that went beyond memorizing equilibrium expressions. Through a simple chemical symbol, the depths of chemical understanding can be plumbed by connecting the molecular-level and macroscopic-level representations.

A common illustration of this is LeChatelier's principle, commonly taught in a general chemistry lab. This is often used to explain why a stress in a system at equilibrium results in a shift to counteract the stress. While this interplay of stresses and shifts may not be visible at the atomic level, an accompanying color change connects the macroscopic representation in such a way that a student could make conclusions about what was happening at the atomic level. This theme will be explored in the following chapter.

By examining the intersection of student explanations with the macroscopic evidence, it was possible to draw further conclusions regarding the specific ideas they held. A big opportunity for analysis of student thinking was through these lenses of dissolving and dissociating. In particular, during Steps III through V of the interview, students were given opportunities to verbalize their thinking by generating ideas, and presenting conjectures in relation to the mixing of HA with H_2O.

The results from this study point out that the semantics of terminology are actually masking a great problem. Students are not merely incorrectly using the terms of 'dissolve' and 'dissociate' interchangeably, but even more fundamentally, they are failing to recognize when both events are occurring simultaneously. Through the proper usage and explanation of symbolic representations, students could learn to distinguish between the two, thus opening the way for a strengthening of conceptual understanding in this area.

The goal of this chapter was to explore students' use of multiple representations to resolve conflicts when faced with distinctions between a solid and aqueous phase of a substance. In Step IV of the interview, it became clear that the puzzling scenario created by the experimental data caused a conflict between what students expected based off a chemical equation and what they witnessed with experimental data. This scenario was used as a measuring stick or indicator of how well students' connected macroscopic and molecular-level representations. The next chapter will examine another difficulty and student successes as they sought to explain an observable property with an invisible molecular-level model.

Chapter 5: Resolving Conflict between Macroscopic and Molecular-Level Representations - Viewed through the Lens of LeChatelier's Principle (Color)

Introduction – The Conflict

This chapter focuses on how student descriptions of color illuminated a difficulty in their understanding of chemical behavior at the molecular level. Students' ideas about expected colors revealed a conflict in what they understood about what was occurring at the atomic level. As described in the previous chapter, during Step III of the interview, two distinct colors began to appear upon addition of solid to liquid: first red, then yellow. The conflict for students was that the red color supported a view of a dilution whereas a yellow color supported a view of the formation of a new species.

As described in the previous chapter, two types of models could be used to account for the behavior of the chemicals at the molecular level. Successful student understanding came from recognizing that both models were influential in understanding the given equation. For example, as seen in the given equation, the phases of matter were not identified for students. If this was not recognized, this created some ambiguity as they attempted to understand the developing experimental evidence. Success in reconciling the given equation with experimental evidence depended on resolving what each term of the symbolic equation represents.

$$HA + H_2O \rightleftharpoons A^- + H_3O^+$$

This chapter will proceed by using Step II of the interview to establish a baseline by examining student ideas based on their drawings and corresponding comments. A ranking exercise in Step III provided further insight into how students understood the molecular-level representations. A subset of student interview data from Step IV was then analyzed to reveal the various types of ideas that students have in terms of expected colors. The discussion revealed that in Step V, LeChatelier's Principle could be used as a tool to illuminate student difficulty in understanding an expected color change. Finally, a PhET visualization in Step VI of the interview was used to clarify that two species were actually present (red HA and yellow A^-), as opposed to one species that was orange in color.

By the end of the six steps of the interview, the symbolic-level representation was manifested as a vehicle or a bridge for linking and understanding the other two representations (macroscopic observation and molecular-scale views). Successful students were able to generate a set of normative chemical symbols that correctly explained the physical phenomena. Through the use of color as a link to the macroscopic observable representation, student understanding of what was occurring at the molecular level was illuminated.

Differentiating Colors - A Baseline (Steps II and III)
Generation of thinking by drawing representations was shown to be advantageous in helping students understand dynamic visualizations (Zhang & Linn, 2011) and texts (Leopold & Leutner, 2011). Thus, a drawing exercise was incorporated as Step II to help students think about the relative amounts of species present. In Step III, they were then asked to associate these species with colors and rank relative amounts. Thirty-one written samples of student work were analyzed and are presented here.

The background for this study had come from a series of pilot interview case-studies (Daubenmire & Stacy, ACS 2011). During these interview studies of undergraduate chemistry learners, it was revealed that a set of students had never been exposed to multiple representations of dynamic visualizations. Those students who had encountered simultaneous dynamic representations during the course of a class were able to generate more explanations for how these representations were linked together. In this instance, the mere lack of exposure to multiple representations was significant enough to limit one's ability to connect between these representations.

Step II - Students Drawing into 4 boxes
During this step of the interview (Step II), students were asked to draw what they associated with the given equation. This involved asking them to generate drawings over a period of time that described what might happen when a solid was added to liquid. These students were asked to generate what this process would look like 1) before, 2) slightly before, 3) slightly after, and 4) a long time after addition of the solid. These drawing steps illuminated student prior knowledge about relative amounts of species present (Zhang & Linn, 2011).

Drawing Representations
Four major distinct characteristics of representation were identified in student drawings, as summarized in Table 13. These results are presented to strengthen the conclusion that these students had a reasonable and appropriate level of prior knowledge as it related to the Given equation. Description of comments that students made about the characteristics of HA in these steps are summarized in Appendix D. Classifications were based upon the most common (3 out of 4 boxes) representation for each student.

Seven students (ATOMIC, n=7) used some type of ball and stick or space-filling representation as a normative way to represent atoms at the atomic level. A second category of students (SYM, n=7) depicted the reaction symbolically using only letters, without referencing any type of bonds (using straight lines) and without connecting atoms together into molecules. The third category of students (MOL, n=15) used any number of ways to depict the molecules, but uniformly used more than one instance of their chosen depiction to complete their models i.e. a copy and paste effect. A crucial subset of this third category included ten students who created their own "bonded letters" notation– letters connected to each other by straight lines to depict molecules. (Two other students were not categorized due to their use of multiple incomplete types of drawings.)

Table 13. Characteristics of drawing of representations

Code	Description	Students (n=)
ATOMIC	Single occurrence of space-filling or ball-and-stick models	7
SYM	Single occurrence of Symbols or english letters	7
MOL	Multiple depiction of either ATOMIC or SYM	15
Subset of MOL	Multiple instances of "bonded letters"	10

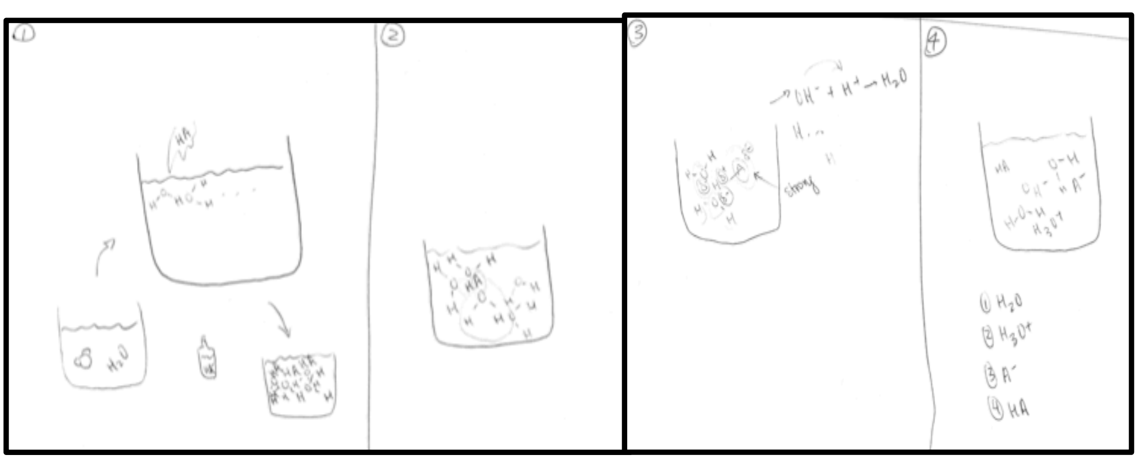
Multiplicity

Textbooks commonly illustrate only single atoms, thus leading students to expect individual atoms to have properties appropriate to an aggregate of atoms (Ben–Zvi et al., 1988; Yezierski, 2006). Bucat and Mocerino (2009) had pointed out that misconceptions arose from students examining a single particle perspective, most likely since this limited them from noticing what happened when individual atoms interacted. Interestingly, whereas most students began by depicting only one molecule or atom, as the activity progressed, many transitioned to depicting one, two or even more HA molecules. (There was one rare case where a student began with several HA depictions, but by the end of the drawing exercise, had reduced down to one depiction, perhaps because of tedium or repetition)

Over the 4 boxes of the drawing step, 16 students were found to have retained their characteristic way drawing throughout all 4 boxes, while 7 moved from a single occurrence to a multiple occurrence model. This occurred most often in the fourth box, where it became necessary to depict multiple occurrences to represent the equation over time. In addition, 8 students changed from one preferred single occurrence representation to another single occurrence representation. The fact that there were changes in these areas indicated that the generating of these drawings helped students to think about their own understanding of this representation.

Below is a sample work of student 4B24, who actually progressed from a simple atomic-level view of HA in a (macroscopic) beaker in the first drawing to a "molecular-level" view depicting H_3O^+ and A^- as ions in solution in the fourth drawing.

Figure 4: Ideas Generated by Student 4B24 during Step II



Macroscopic Representation

In this step of the interview, only 13 out of 33 students drew a macroscopic element to indicate that this equation was taking place with some element of a real world connection. Macroscopic was interpreted to be drawing 1) a beaker or other container, 2) showing an aggregate of solid at the bottom of a container or 3) representing the solvent level relative to the height of the drawing space, thus distinguishing between visible phases of liquid and empty space. This type of depiction drew attention to the fact that students were thinking about how this related to an observable scenario.

Step III - Color of HA and A^-

This section of analysis looked at student ideas regarding colors of the involved species. After completion of Step III, when the solid HA had already been added to water, students were asked to judge what color each species contributed to the color of the overall solution.

Since H_2O and H_3O^+ would be colorless, it was left to reason that two visible colors would result from the remaining two species HA and A^-. A handful of students had conceptual difficulty in determining the colors of H_2O and H_3O^+, and required a longer amount of time and consideration to finally determine that these would be colorless. Others, as seen below, conflated the distinction between the macroscopic color of the solution and that of the individual molecules.

Student 4B21, Line 233

> S: So before we will have this, and the water will be clear, and after we mix them, it more or less retain the… I would say it's orange. Water will be amber color. I am not sure if you can separate this (pointing to A^-) and identify color, because this is technically dissolved in water, so I guess you can just say that they are the color of the water.

Predicting Initial Color

Students were asked to describe the initial appearance of HA and 20 students used "red-orange" or a close variant. 7 students used "red" as their initial color. After the addition of the solid to water, an additional species of A^- was generated. In examining the new solution, students were asked to predict the color produced by the A^- species. 17 students described the color of A^- as "yellow-orange," 7 described the color as "red" and 4 described the color as "yellow."

Table 14. Occurrences of Student Description of Initial Colors

Initial HA (n=)	Description of Color	After Adding to H_2O (n=)
20	"red-orange	0
7	"red"	7
n/a	"yellow-orange"	17
n/a	"yellow"	4

Of particular interest in this area of analysis were the 17 students who used "yellow-orange" to describe the color contributed by the A^-. Upon further analysis of the interview data, it was revealed that though students identified a color as "yellow-orange," they had differing explanations for why the colors were such. While this was not an intended effect of the interview, it provided a lens into student thinking regarding the species present in solution, as well as the origin of color of sub-microscopic particles.

Dilution Supporters

A first group of students represented by Student 4B8 believed that when "reddish-orange" HA was added to the water, the color of the resulting "yellow-orange" solution was due to the dilution of HA in water. As seen in the data below, a variety of ideas came out.

Some students believed that a diluted combination of red-orange would contribute to make a yellow solution.

Student 4B8, Line 165

> S: So this is the stronger orange-red color (*pointing to the vial of solid HA on the left*); and, this (*pointing to H_2O*) is clear, so I think it (*pointing to H_2O*) dilutes the rest of the orange color. That (*pointing to H_3O^+*), I don't think it changes the color, it just remains clear. And I think, if this dilutes the red-orange color, then…
>
> Line 180
>
> P: So let me contribute in this. When you first saw this, you said, "Oh, this is slightly yellow." Where is the yellow from?
> S: The yellow will be from the dissociation of this (HA), so yeah. I think it would be the red-orange color and the water dilutes it to make it yellow.
> P: Okay. Yeah.
> S: …diluted by water to become yellow.

Others correctly pointed out that the contribution of individual species may have an influence on the overall color.

Student 4B21, Line 239

> S: …I would say as a result of mixing HA and H_2O, the colors of these individual molecules or ions have these particular colors.
> P: Okay, that's right. So if I were to ask you, "What does each of these contribute, if I were to say HA makes it ______, A^- makes it _______, what would you say?"
> S: So this [gesturing at HA] is same as before, H_2O remains clear. It's less of the contribution. But on the other hand, HA was brown-red, so I guess the water dilutes it? And that's why the water appears amber and this appears lighter, it went from brownish-red to red-orange.

At this point in the interview, even though they had been prompted by the given equation, many did not have a persistent understanding that a second species A^- had been created. In trying to reason that HA had been diluted, it was more apparent that they were having difficulty in identifying the effect of A^- on the color of the solution. It is also fair to say that students generally lacked a reasonable understanding of dilution.

As seen below, a student reported that producing A^- (conjugate base) would have no effect on the color of the solution. His final comments seemed to imply that dilution would have no effect on color.

Student 4B2, lines 138-156

> S: I think that it's going to mostly dissolve, pretty much completely dissolve.
> P: Okay, so it's going to mostly, completely dissolve. What other properties would you expect? What color, what clarity?
> S: … <u>it would probably still be slightly red because I would assume that the conjugate base if it dissociates according to this (*pointing to Given equation*) reaction, it's still going to retain its color, so it'll be slightly red.</u>
> P: Okay. So this will retain the color (*pointing to red-orange solution*). What would you expect this color to be (*pointing to A^- on paper, at the end of equation*)?
> S: It would be the same color, I'd assume.
> P: And then you mentioned, "depending on how much dissolves." Why is that important?
> S: <u>Because if you put a lot of water in there you're not going to notice a big difference in the color of the water, I'd assume. Not noticeably enough that you could determine whether a more concentrated solution would have that color or not.</u>

New Species Supporters
A second group of students presented data that the species A^- contributed a different color than the species HA, yet they also they described this color as "yellow-orange." While they also grappled with the color change, in their interviews, they incorporated the symbolic equation into their understanding. Even if the data could have seemingly supported a dilution-based explanation, their interpretation of the symbolic representation (the Given equation) involved identifying A^- as a species capable of contributing a "yellow-orange" color.

What is Yellow?
From the perspective of the analysis described in Chapter 4, a solution that contained HA that had been dissolved and then dissociated into A^- ions was the true source of the yellow color (actual). However, as seen above, a significant number of students imagined that HA that had been dissolved was the only source of yellow in a solution (perceived). Thus, even though a yellow color was the baseline for dissolved and dissociated HA, for some students, they (wrongly) perceived and described a "yellow-orange" color as "yellow," when in actuality it contained a contribution of red.

Because their baseline had wrongly been established as yellow (as opposed to "yellow-orange"), these students then struggled with their description when the solution in actuality became more yellow as it was diluted further. This addresses issues of the language of science as students try to distinguish among their ideas, as well as student confidence in their observations and perceptions.

Further work in this area should involve looking at these two groups of students in order to see if there are any ways to disambiguate them from each other. For example, it might be possible to examine and identify the initial colors that students use to describe HA, in order to determine if there were any distinctions between them. For example, were students who described HA as "reddish-orange" less likely to see a color distinction than students who initially described HA as "red?" Does student preference for drawing an atomic-level representation carry over in being able to see the distinction?

Step V - Predictions from LeChatelier's Principle

Le Chatelier's Principle has been widely cited as a manner for helping students understand the dynamic and reversible nature of an equilibrium reaction. It has also been cited as a method for teaching students how to quantify the change and direction of a shift when a stress is placed upon a system in equilibrium. It has also been singled out for creating student difficulty because it requires students to explain the unobservable molecular level cause of an observable macroscopic level phenomena such as a color change (Wu, Krajcik & Soloway, 2001).

Thus, this analysis proved to be a crucial consideration for students during Step V of the interview study. During this step, it was clear to 100% of the interviewed students that by addition of H_3O^+, a product species, the expected result would involve a shift to the left i.e. formation of a reactant species. LeChatelier's principle proved to be the transition point in this interview, particularly in exposing which models students were working with, as well as the types of ideas that students held. This was the classic "lightbulb" moment during the interview, where it was possible to gain insight into what students had been thinking throughout the course of the interview, and perhaps when they could distinguish between ideas and discard some. Thus, the coding model for this particular section involved asking students what they expected to see with the shift back to the left.

As student after student invoked Le Chatelier's principle, it was realized that students might not have actually understood what species they started with. That invocation revealed that some expected that the solution would go from being yellow to expecting to see a red solid crystallize. Rare was the student who expected to see any type of transition back to a red liquid only. Several students were stumped and asked if any indicator had been added to the solution. As HA is by definition an indicator, they were assured that only the given substances were added to their experiment

For many of these students it had not previously troubled them that there were no states or phases of matter written. (This might have encouraged them to think about the properties of group of molecules -like of a solution– rather than of individual molecules. Upon being asked to generate corresponding colors, there was no one who immediately recognized that HA was given to them in 2 different forms: one form being solid, and one form being aqueous, a dissolved solid – yet that they both would be red. It was also realized that some students kept track of this dilution as it progressed from a previously darker orange to now a lighter yellow orange in Step III. They recognized that by adding the water in Step IV, a color change might be expected, but not necessarily a phase change.

The difficulty in discriminating between these two groups involved some students believing that red HA diluted in water took the color of “yellow-orange.” Other students believed that A^- was a different color from dilute HA, yet this color was called “yellow-orange” (A future study could tease out the distinction between the two.)

Results of Reversing the Reaction

Thus, the coding model for this particular section involved asking students what they expected to see with the shift back to the left, and from analysis of the data, three explanations predominated. One group of students expected that according to their understanding, the initial red solid (corresponding to HA) would reform. This correlated to what they had initially observed, in that HA was added to water as a red solid. For them, the reversibility of the reaction lent itself to the discussion of Models in the previous chapter. Upon addition of H_3O^+, there was a general expectation that the solution would turn from yellow to red. However, there was some conceptual difficulty for students as they struggled to consider if solid HA would reform. A second group of students expected that there would be a shift towards a red liquid or solution, but that they did not necessarily expect formation of a solid. Finally, a third group of students predicted that only a darker yellow solution would result.

While not immediately apparent, there is also the possibility that some students happened to observe the experiment in more detail, thus equipping them to describe the microscopic representation more clearly. The implications of this type of thinking will be examined in the next chapter, where a student’s difficulty in interpreting the symbolic equation correlate to their ability to make sense of the interview content.

Step VI – Using PhET to Shift Between Red and Yellow

During Step II of the interview, students were asked to integrate their understanding of the given equation by drawing their own simplistic visualization over four different timepoints. By establishing such a baseline, then allowing them to work with the PhET visualization in Step VI, it had been possible to make some comparisons for how well they integrated their prior knowledge. In addition, it allowed for a stronger comparison between how well they linked the macroscopic property of color with the molecular property of identity of a species.

Color as a Property

One curious outcome during this step of the interview was the suggestion made by numerous students that because of the yellow-orange solution in front of them, they expected to see orange particles in the visualization. This flawed idea came from their expectation that a yellow-orange solution would be generated from the mixture of a yellow and an orange solution, as opposed to a yellow and red solution. They wanted to see macroscopic properties reflected in the individual atoms. Rather than thinking of orange as a continuum between two colors due to two different species, weaker students expected all individual atoms to be orange. Thus, they failed to make the distinction between color being a property of individual molecules and color being a macroscopic property related to an entity (Ben–Zvi et al, 1987). These students wanted to see orange, and when looking at the visualization, they wanted the individual molecules to appear orange, as opposed to being yellow and red. While this is not a significant matter, by the end of the interview, they were able to link these concepts of color together with the change at the level of symbolic representations.

Description of PhET interview portion

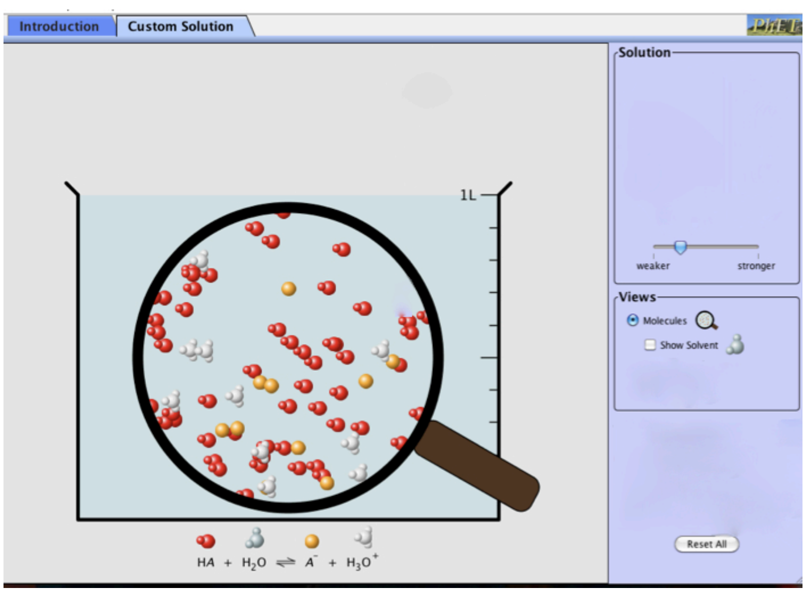
The PhET visualization was used with a slider that appeared to control the concentration of A^- and HA. Indeed, as the slider was brought the far right, the quantity of A^- molecules on the screen increased until the slider stopped, seeming to indicate that the extent of the forward reaction was determined by the boundary of the slider.

However, when the slider was brought to the far-left, this did not represent the equilibrium being shifted to a starting condition where there were reactants only. Instead, the slider only needed to be brought to a point where it was approximately 1/5 of the distance from the left side to accurately convey the "finished" reaction as demonstrated in the experiment. This fit in with Ainsworth and VanLabeke's work (2004) that pointed out that multiple representations could be time-persistent, time-implicit or time-singular. By constraining time as a variable in the time-singular constraint, it would make it easier for a student to make sense of the data.

Visualizations conveying multiple representations

The main goal of this exercise was to examine the verbal comments made by students as they examined multiple ways in which a chemical phenomena was represented. As seen in Figure 4 below, all three levels of representation were depicted simultaneously. In addition, the given chemical equation represented symbolically at the bottom of the screen, the molecular level was represented using a space-filling model or sphere. In addition, the macroscopic/observable level was represented by the colors of the model.

Figure 5. Screenshot of Modified PhET Visualization



To an expert-level chemist (as described by Kozma and Russell), these three levels of representations could be easily connected to represent the same phenomena. During the course of Step VI of the interview, students were able to demonstrate relative fluency and aptitude with recognizing and connecting across these three levels of representation. As seen in comments from students, their behavior and experimentation with the PhET visualization indicated that they understood that there was a link among the three representations that they had not previously commented on.

Resolving the Conflict

The use of color as a variable presents a powerful tool for discerning student understanding of equilibrium. In a typical general chemistry laboratory setting, students are presented with multiple opportunities to make observations and draw conclusions based off of simple observables, such as precipitates forming and colors changing. While relevant, rarely is this discussion linked back to energy, wavelength or frequency, taught as the mathematical origin of color. Students find themselves exploring color, but often not associating color as a specific property of a substance or molecule.

A real question revealed by this research was whether students actually knew that their observation of colors revealed a conflict in their connecting between the macroscopic and the molecular levels of representation. Most students had commented that the expected prediction for the dissolution of a red powder would be a red liquid. When the actual addition of the red powder occurred, most students noticed and commented on the yellow color change of the liquid. Others noticed the red wispy tails that trailed behind the dissolving red solid. However, nearly none offered any explanation at this point that incorporated a mention of a change or shift in equilibrium. Thus, it was quite apparent that the majority of students were not actively linking the macroscopic with the atomic representations without further guidance.

At the conclusion of all the steps of the interview, students were asked to generate an alternate way of representing the given equation that would incorporate what they had observed in the experiment. An answer coded as successful was determined to be one in which students accurately wrote down a form of an equation where HA (s) was somehow shown to be converted into HA (aq). While some intermediaries involved the separate H_3O^+ and A^- ions in the aqueous state, the majority of responses represented HA (s) $\rightarrow$ HA (aq). Of the 30 interviews that were analyzed through to this stage, 18 students recognized this as relevant enough to write it down on their written paper. Thus, they had recognized that HA existed in two physical states of matter, but that HA alone was responsible for contributing only one color.

To go one step further, it was a significant overcoming of conceptual difficulty to recognize that the color of a solution was based on the colors of the individual components in that solution. Two different species might contribute two different colors. Thus, an orange solution did not necessarily result from the dissolving of an orange particle, but from a dissolved mixture of red and yellow particles.

This confronts the errant conception that the identical species can change its color during the course of a chemical reaction. This conflict was resolved in this experiment through exposing students to the difficulty in understanding the symbolic representation, and forcing them to realize that, of all the species present in a given solution, two of them were responsible for contributing different colors. By recognizing this, they could be afforded a way to make sense of the chemical symbols at a molecular level. Ultimately, this was a demonstration of how students could be helped in rationalizing their experimental observations with microscopic explanations, even when they had been initially confounded by symbolic representations.

The next chapter will examine how students achieved this kind of success through the act of conjecturing –proposing verbal statements that advanced hypothesis. It will be possible to characterize successful conceptual understanding of simultaneous multiple representations by examining several sets of students and their success in understanding the interview study.

Chapter 6: Conjectures and Pathways

Introduction
The goal of this chapter is to reveal pathways of conjecture usage to explain why students could explain an individual occurrence of a representation, but then not be able to discuss the connectedness among different manifestations of the same representation. Even though students could produce viable and meaningful responses for individual steps based off their understanding, some still struggled to verbalize how these steps conceptually related to one another. It was hoped that verbalizing conjectures became an effective intervention by priming or cuing students to use symbolic representations appropriately. After evaluation of student interview responses, four pathways of conjecture usage were detailed.

Past chemistry education researchers have pointed out that the richness of student responses diminished when algorithmic questions were asked (Teichert & Stacy, 2002; Rupert, 2001). Through a particularly focused study, specific conceptions of student thinking could be gleaned. These ideas, called facets, could then be used as building blocks for students to formulate other productive and normative ideas (Hunt & Minstrell, 1994; DeBarger *et al*, 2009; Chang, 2009) It was found that this interview study allowed every subject to access productive thinking and to generate some type of drawing or artifact to describe their ideas.

The interviewer was seeking to uncover student ideas in the form of conjectures. Conjectures were needed to facilitate the connection of ideas. A conjecture is defined as a statement or verbalization of ideas that can either be proven correct or incorrect. While it functions as a hypothesis, it does not have the characteristic of necessarily being based upon evidence. Rather, a conjecture is a statement that can be proven correct or incorrect through the examining and assembling of evidence and existing beliefs.

My hypothesis is that without advancing a belief or verbalizing an idea as a conjecture, even if there is adequate conceptual or background knowledge, students have less success in connecting their ideas across different representations to solve problems.

Why were students not able to translate across these different representations when they had success in the individual components? If they had success in the individual components, one would expect that there would be some kind of connection across all the representations, but instead, there was success in individual components and a lack of connecting, or even more, a shortage in fully understanding the individual components.

The goal of the interview study was not to rank students according to their knowledge, but rather, to see how successful they were in integrating their understanding from all of these ideas. It is argued in this chapter that conceptual understanding comes not only from having successful ideas or even sufficient prior knowledge, but the use of conjectures to choose the ideas that will lead to a correct and connected understanding.

Compartmentalized Instruction
One aim of this interview study was to allow students to make statements about familiar material that they were encountering in unfamiliar situations. This required students to consider whether the information was connected, since it appeared to come from different subdomains of chemistry. For many students, this information was not necessarily connected in their minds, as it has typically been taught in compartments in their texts and courses. As it turns out, student molecular-level ideas exhibit context dependence (Teichert, et al., 2008). Even more specifically, students' ideas about aqueous solutions at the molecular level are even more highly context-dependent.

The interview study developed in this dissertation afforded students an opportunity to connect their ideas from among different sources. Even when they had contradictory ideas, the context affected whether molecular-level ideas were remembered or brought up. After they had generated some ideas, they could evaluate this information, choosing the relevant facts that would strengthen the connection of this material to their existing ideas. Thus, they were systematically led through multiple representations to help them integrate their multiple ways of thinking about the same subject matter.

Conjectures in the Interview
Conjectures are ideas generated by students in response to prompts by curriculum or instructors designed to lead them towards a hypothesis or conclusion. They are more than just ideas generated by students in response to stimulus or prompts. Conjectures are students' attempts at verbalizing their thinking on their way to forming a hypothesis.

Student conjectures were identified during the initial steps of the interview, as documented in Appendix F. During the second step of the interview, students were asked to generate their ideas related to a given expression. They followed this discussion by generating drawings in response to certain prompts. While this initial step allowed for establishing a baseline of what students were thinking, it also gave students the opportunity to conjecture.

Furthermore, it is not so much the content of students' conjectures as it is the act of conjecturing that differentiates successful students. The behavior of conjecturing will be revealed as being meaningful in bringing about student understanding. Thus, the goal of instruction should be to help students translate observable properties or observations into atomic-level representations. By giving them opportunities to make conjectures about the relevance and appropriateness of their understanding, an effective intervention appropriately primes or cues students to use symbolic representations.

Analysis of Student Behavior in the Interview
In this interview, students were asked to generate ideas. However, this was not just a passive step of describing what they observed with their senses. Rather, during the course of the interview, they were asked to connect what they saw with what may have actually been occurring at a molecular level. This required them to not only consider what they were seeing, but even more, to verbalize how what they were seeing connected with what was actually happening.

However, when faced with new experimental evidence and asked for initial ideas, there was less an element of reflection, and more of an element of idea generation. In line with these previous ways to discuss student' approaches to thinking metacognitively, students in this interview study were asked to 1) generate ideas, 2) interpret experimental evidence in light of these existing ideas, and then 3) incorporate or assimilate this new information into their existing ideas. There were three areas of this interview study that stood out as distinctive in their potential for fruitful insight into student thinking. These areas provided multiple opportunities for students to make conjectures and predictions based off of their prior knowledge and conceptual understanding. How these areas correspond to the Steps of the interview is described below.

The first category of analysis correlated with topics covered in Steps I and II of the interview and focused on *Generating Ideas*. Here, students were presented with the Given equation, and asked to interpret the equation, as well as generate hand-drawn representations according to their understanding. In the course of this analysis, it was possible to see how prior knowledge and pre-existing ideas influenced students' conjectures.

The second category of analysis correlated with observations and insight emphasized in Steps III, IV and V, and focused on students' *Interpretation of Experimental Evidence*. A series of experimental steps was performed that resulted in color and phase changes, and students were asked to verbalize their observations, as well as make conjectures about possible outcomes and rationale for the phenomena. These predictions were necessary for students to make sense of the data, but also adapted as the interview progressed.

The third category of analysis covered Step VI and correlated with students' revisiting the Given equation, with the view of *Incorporating New Information* that they had been exposed to into a cohesive understanding. This is not just a revision of their ideas necessarily, but rather an attempt to make their thinking coherent by linking ideas. Also, through use of a PhET visualization, students had the advantage of another representation with which to explain the physical phenomena that they had just observed.

In these interviews, students were asked to predict what they would expect from a given equilibrium statement. By priming the students with a standard equation, it was possible to frame the discussion and understand more clearly the model or ideas they were using. Secondly, they were then exposed to experimental evidence that challenged their understanding of this model. Then, through the prompting of the interviewer, as they verbalized their thinking, they had to compare and contrast their observations with their earlier ideas. Finally, based off of their explanations, they were given the opportunity to come up with a more integrated and cohesive model, explaining and rationalizing the experimental evidence with their understanding.

The following section will discuss the types of responses generated by students, both negative and positive. Excerpts from the student interviews will be used to demonstrate how the interview subjects were thinking about the representations presented to them. It was quite common to find that a given student would excel in communicating their understanding on one part of the interview, and then fail to adequately explain their thinking in a subsequent part. Thus, it became important to look at student performance during the interview by examining their most sophisticated thinking. Though a student may have struggled with a part of the interview, the goal was not to expose inadequacy in the subject matter.

Throughout the interview, the interviewer specifically refrained from affirming or denying a student's ideas or claims. This led to occasional hesitation, as students were not receiving immediate confirmation or feedback to their statements and hypothesis. In these cases, the subjects were told to list all possible scenarios or possibilities for explaining a phenomenon. Most, though not all, of the time, students would then select one of these explanations as satisfactory and plausible. In addition, when the students seemed to hesitate in providing explanations, the interviewer would ask a question encourage the student to continue verbalizing their thinking.

Summary of Four Pathways

Four types of pathways were identified through analysis of student interviews and are summarized in this chapter. The goal of this analysis was to systematize and illuminate student thinking as revealed in the interview, with a view towards characterizing student success in connecting among the representations revealed in the steps of the interview. Student interviews were completely transcribed, time-stamped, and line-numbered.

A number of questions were asked during analysis of the written transcripts. First, what were the conjectures that students actually presented? Second, did students modify their conjectures as more evidence was introduced? Finally, to what degree were they flexible in being willing to modify their conjectures? In other words, was there any measure of confidence expressed in their conjectures? Students sorted into approximately four categories, as outlined in Table 15.

How successful are student conjectures in terms of connecting multiple representations? The following table demonstrates four pathways of student thinking characterized by four types of conjectures. Technically, there are three types of conjecture, with the fourth pathway being students who lacked in generating any type of conjecture.

Table 15. Four Pathway Framework for Analysis of Interviews

Level	**Generating Ideas (Four Types of Conjectures)**	**Interpretation of Experimental Evidence**	**Incorporation of New Evidence (when faced with new evidence)**	**n = %**	**Success of Conjecture (Connectedness)**
1	Lack of any Conjecture (doesn't know where to start!)	Initial evidence left students with unclear starting point	New evidence further overwhelms/confuses	6 23 %	Inconclusive (not successful)
2	Wrong Persistent	Previous conjecture	Additional data is discarded/ignored	4	Inconclusive connectedness

	Conjecture-contradicts data, but persistent	persists (student talks about new evidence through the lens of their previous/old model)		15 %	
3	Wrong Revisable Conjecture-contradicts data, but revisable	Previous conjecture abandoned or revised	Additional data causes revisiting and revision of conjecture (so what do I know?)	8 31 %	Conclusive connectedness
4	Correct Normative Conjecture-matches data (consistent with normative explanation)	Previous conjecture pursued	Additional data strengthens	8 31 %	Conclusive connectedness

Four Levels of Connecting Across Representations

Level 1 student –Weak or No Conjecture (Lack of Background Knowledge)
The lowest level student evidently struggled with verbalizing and describing his or her ideas. Though a student at this level could have had many individual ideas, they would have struggled with cohesiveness. More commonly, a student at this level would be described as a "weak" student – one with a limited background knowledge. (This is having passed a college general chemistry course with an A or B) As pointed out by Zoller (1996), this interview served as an assessment to distinguish students who had "no conceptions" versus mere misunderstandings.

Level 1 Student Sample Data (n=6)
Students in this group manifested their lower level in several ways. They could have been very limited or poor in their approach to the interview, suffered from a weaker foundational knowledge, or verbalized less integration with existing facts. Sample behavior includes students trying to verbalize chemical relevancy to irrelevant topics or regurgitating memorized facts.

It's easy to see how this first category could come about where individual ideas would give students difficulty and as a result of that they would have no chance of seeing the big picture. In terms of the actual interview, these students could be described as "lost," not seeing the connectedness as they moved from one step to another. Thus, if a student struggled with one specific individual idea, it could jeopardize their capacity to understand the big picture. As a result, they would be "dragged" through the interview study with a difficulty in understanding one of the prior five steps. 5 students in particular manifested characteristics like this during the interview.

Level 2 student –Wrong Persistent Conjecture (Unwilling to Change)
Unlike the first group of students, this second category of student was able to generate conjectures regarding their ideas. However, as the interview progressed, their initial ideas persisted in such a manner that new experimental data were not assimilated or integrated. Rather, their ideas were ignored, set aside, or even possibly discarded. Thus, these students were categorized as generating "persistent" conjectures that were individually reasonable, but that contradicted experimental data. These wrong, but persistent, conjectures ultimately did not allow students to generate a cohesive understanding across representations.

As an illustration, student 4B7 would make conjectures, but would experience conflict when the experimental evidence he/she examined did not support the conjecture. Students in this category would allow a particular feature of the experiment to dominate their considerations, leading them to have difficulty with the overall interview study.

This type of student was not necessarily conceptually weaker than students classified as one of the other pathways, but merely more likely to focus on another feature of the interview that caused them to have difficulty. 4 students in particular manifested characteristics like this during the interview, and were thus classified using a specific code.

As an example, student 4B2 conjectured regarding the cause of color of an ion, and attempted to use the evidence to support his hypothesis. The student's point was that the color of an ion would be the same as the molecule from which it was formed. It's unclear what the origin of this conclusion is, but there was a rigid unwillingness to modify or abandon this consideration. While this was not based on experimental evidence, as seen below, he chose to support his hypothesis in the face of continuing contradictory experimental evidence.

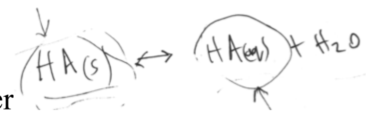
Student 4B2, Line 143 (Before adding more H_2O to HA)

> S: Depending on how much water, it would probably still be slightly red because I would assume that the conjugate base if it dissociates according to this (*points to Given equation*) reaction, it's still going to retain its color, so it'll be slightly red.
> P: Okay. So this will retain the color (*pointing to water with fleck of HA*). What would you expect this color to be (*pointing to A^- on paper, at the end of equation*)?
> S: It would be the same color, I'd assume.
> P: And then you mentioned, "depending on how much dissolves." Why is that important?
> S: Because if you put a lot of water in there you're not going to notice a big difference in the color of the water, I'd assume. Not noticeably enough that you could determine whether a more concentrated solution would have that color or not.

Line 181

S: Well, if it didn't completely dissolve immediately, it means it's probably not dissociating immediately in the water because when you add it to water it can dissolve and stuff, but maybe some of the properties of that HA sort of complex sort of is not hydrophilic.

Line 281 (Before adding HA)

S: What's happening there? (Writing on paper 
) So then I would think that that particle is sort of separate reaction where there is solid and then it's going to aqueous. So then that is another equilibrium reaction, and different solubility constant. So whatever that is not necessarily hydrophilic enough to dissolve in that much water.
P: So this is really intriguing to me. You have the HA with the (s) and the HA with the (aq). Just in your own words, what does that mean?
S: Well, I mean there is a certain amount, depending on the properties of the material that you are adding to the water, it could be more closely attracted to itself than it is to the water, so it won't dissolve into the water. So this (pointing to HA(aq)) is sort of particulate, it is sort of, I mean, atomized in the solution so it is completely surrounded on all sides by water. Whereas this (pointing to HA(s)) is at least touching itself somewhere. It's in clumps, clusters. It can't count as like a molecule in a solution of water.

Line 348-360 (Before adding HA)

S: …and this guy (A^-) I'm not so sure about.
P: Could you make a guess?
S: I mean, I think that it is still red because I think that having that hydrogen on it doesn't necessarily change it too much. So I mean, the color, I think it could most likely stay the same. If it changes that would be interesting.
P: And so then the A^-, you are thinking it'll still be red, HA will still be red and these two (H_2O, H_3O^+) species will be clear. Then where does the yellow come from?
S: Well, so the yellow is just, I think, the red stuff, but it is just sort of spread out and so then when it is not so concentrated in the water it appears yellow. Sorry, yeah.

Line 405 (After adding HA)

S: Surprising to me was that the HA and the A- have really different colors. That's pretty interesting. I'm not really sure what that would reveal about the properties of the molecule, but if you knew a little bit more about that, you could assume some of the properties. Well, we know that it's pretty hydrophilic because it can completely dissolve into the A- form, and that the addition of a single hydrogen changes its color so it can't be that large of a molecule.

Another student (4B8) conjectured that a diluted red-orange color would produce a yellow, and eventually clear solution. As seen below, the student explained that red-orange would be diluted to a yellow color. Later, the student had the capacity to reason about the data using LeChatelier's Principle, and eventually the student was even unwilling to regard the experimental evidence and abandoned correct knowledge about the chemical principles at work. Unwilling to drop this conjecture, the student persisted in rationalizing that a diluted color would result in a clear solution.

Student 4B8, Line 165

S: So this is the stronger orange-red color (*pointing to the one on the very left*); and, this (*pointing to* H_2O) is clear, so I think it dilutes the rest of the orange color. That (*pointing to* H_3O^+), I don't think it changes the color, it just remains clear. And I think, if this dilutes the red-orange color, then…

Line 180

S: Exactly. This means assume this is a weak acid, so this is not favored. But I believe there is some dissociation. So, it means that there are some ions in the solution, and they can contribute something; it could be clear, but it could red-orange. Either way, if it's clear, it will just be diluting that, but that's in a concentrated ball…
P: So let me contribute in this. When you first saw this, you said, "Oh, this is slightly yellow." Where is the yellow from?
S: The yellow will be from the dissociation of this (HA), so yeah. I think it would be the red-orange color and the water dilutes it to make it yellow.
P: Okay. Yeah.
S: …diluted by water to become yellow.

P: So, then, what if we take more color, maybe to get this thing filled. What color do you guess this thing will be?
S: So then … LeChatelier's principle comes into my mind. Which is when you added stress and the equilibrium shifts. So, if you added more water, you added more reactants, which will favor products. So in that case, I think, it would become clear. Because this was a test question from Chem 1A awhile ago. So if this does contribute color, which I said it does, then, you are adding more, you are driving it to the product side, and the color should get stronger, that is what my logic is telling me, but…
P: But?
S: But I want to say it's gonna be clear because the water dilutes it, and that is non-chemistry…
P: Like intuition?
S: Yeah.

Level 3 student –Wrong Revisable Conjecture (Willing to Change)
This third group of students resembled the second group of students in a few ways. They also generated conjectures regarding their ideas, and also found that the experimental data did not match their conjectures. However, unlike the second group, these students did not hold onto their incorrect conjectures, but were able to revise or shift their ideas as they examined new evidence. While their initial conjectures were reasonable, they found that they needed to modify their pathway of thinking once the interview proceeded.

These students were able to make conjectures that were meaningful, and then also modify their thinking in the face of conflicting evidence. Though they may have begun with some "blindspots" in their interviews, such as ignoring the Given equation, they were able to understand individual components of the interview without much prodding and were able to reach a mini-peak in their conceptual understanding where it appeared that they were able to connect multiple representations. In the process of describing their observations, they were also transitioning in their conceptions (hopefully from less good ideas to increasingly better ideas). Thus, one effect of the interview for some students was to transition them away from " forming misconceptions" towards "forming hypotheses" (even if they were wrong).

Level 3 Student Sample Data (n=10)
Student 4B5, Line 19

S: So that, HA, wouldn't be a strong acid, it would be a weak acid, because it doesn't completely dissociate. Well, no, that's probably not true either. Because some strong acids have some kind of equilibrium. Well, maybe not by definition. But I would think that if there is some meaningful equilibrium, it would be a weak acid.

Line 103-104
S: Hmm, the first thing that comes to mind is either it could be soluble and dissolve, or be insoluble and it could be suspended in the solution but it might not be dissociated.

Line 202
S: (16:05; S seems stumped) So HA is undissociated. I don't know, just generally when I think of a weak acid, I think of acetic acid and how it behaves. So there definitely can be undissociated acid in a solution, but this is somewhat different because it started off as a solid, so could it, I'm wondering if it could be solvated but not dissociated. And what color would it be. I know hydronium is colorless. A- I suppose could have a color. Acetic acid doesn't, so that's not helpful. I don't think I know of any acids that have a color. \\ I don't know.

Line 254
S: Okay. \\ (S writing) This is something I thought initially, but there's no—

Line 266
S: I don't know if it was relevant, but once you put the solid in there, then I was thinking, wait, I was initially thinking of this as acetic acid as a liquid. But when there's a solid in there I now have to think of, wait, there's clearly some solid in there. There is possibly some solvated but not dissociated and there could be some dissociated, I don't know.

Line 271
P: Okay, interesting. You made 3 distinctions there. A solid acid, a solid solvated acid, and then a dissociated acid. Okay.
S: Well, does that make sense?
P: When you looked at this (*pointing to Given equation*) equation, which of those did you lean towards?
S: Initially I thought it was aqueous (HA).
P: This is helpful because these get thrown at you all the time, in lecture, in textbooks, and everywhere else, so trying to understand this thought process. So, what do you think will happen if I add more water? And let me stir that up a little. There's still that little speck in there that wants to dissolve, but let's assume it's all dissolved.
S: Okay, if we assume it's all dissolved, and it's not saturated, then if you put more water, then the color should become more clear, and the color less apparent.

Line 327
S: I don't know if I can make that assumption. Now I'm curious and when I go home, I'm going to look it up. If ions can, if ions will absorb light, I assume they could. Well, I don't know if it would be in the visible spectrum. What's the visible, mostly vibration. Is that what would make sense for ions? Well, there's platonic ions. Yeah, I don't know what assumptions I can make. Well, if it's a weak acid, it should be more HA than H3O+ and A-. Is that necessarily true though?

Line 379
S: I really want to know if ions, if dissociated ions can absorb light. I think they can, probably polytonic ions, but I'm not sure. Because I don't know if that color is coming from A- or HA.

Line 434 – after LeChatelier's Principle
S: I was thinking it might be iron oxide, but then this wouldn't make too much sense. Why would it do that? It could be an organic molecule, well, no. I don't think that makes sense. Why would it change color?

Level 4 student –Correct Normative Conjecture

Students categorized in the previous pathway may have generated theories, but at times, lacked key background info that prevented them from directly making sense of the experimental data. This fourth group of students produced conjectures like the previous two groups, but in the process, generated conjectures that were consistent with normative or expert explanations.

Inclusion in this category did not necessarily include the most fast or most confident students. However, these students expressed a cohesive understanding about the content of the interview that was able to lead them to successful understanding. They were able to not only generate conjectures, but also to show one alternative over another in the face of the evidence.

Level 4 Student Sample Data (n=7)

Student 4B17, Line 209

> P:…you mentioned something to me about mixing and stirring. What was your thought there?
>
> S: \\ I was thinking like paints, like powdered paints, when you put them in like this and you add water, you get this water-color kind of color. So I wasn't sure if it was that kind of thing, or a salt, will it just dissolve and it'll stay clear. I was thinking of a color, but—

As an illustration, student 4B17 was a model interview, successfully anticipating both aspects of dissociation/dissolving as well as correlating color changes to the Given equation. This particular student, while not demonstrating immediate understanding of the problem (the student used the word "dissolve" at the end of the quote, when it should have been "dissociate", generated conjectures that matched normative expert thinking and presented multiple view points as the interview progressed. While this category was initially expected to be the least common, a number of students accurately and successfully reasoned through multiple hypotheses, and were able to join the different representations into one connected understanding.

This type of student was a positive example of an introductory chemistry learner's success in generating a conjecture and being able to demonstrate understanding through exposure to multiple representations. This type of student could be used as a model to examine how this type of intervention could successfully be used to connect, to bridge, and to synthesize across different representations.

Another example of a student in this category (4B20) was one who was deliberate in this thinking, but nevertheless advanced his conjectures toward a meaningful hypothesis and connectedness.

Student 4B20, Line 284

> P: What would you expect, or what is some hypothesis of what would happen if you put some of that in distilled water?
> S: \\ I think it would probably dissolve in the water.
> P: So if the powder dissolves in the water, what would you see?

S: If it doesn't, if, \\ I guess, I assume that the water would turn kind of the same color as this (powder) if A- doesn't have different properties, or if it doesn't change color, I guess.
P: So that's interesting to me. You said that this is a red powder, and then you said something about A- having different properties. What are you thinking when you said that?
S: (20:38) Well, there, well in my experience I have used indicators that change color when it is protonated or deprotonated. So, I don't really know anything about this (vial of HA) so I can't really assume too much about what would happen.

How is this helpful for students and instructors?
After consideration of these four pathways, three questions were raised regarding students' use of conjectures. Specifically, 1) it was possible for students to link these representations; 2) Successful use of conjectures depended on ability to connect across representations; and 3) Students were willing to conjecture.

1.) Conjectures depend on the ability to connect across representation
Across these four pathways, student success was measured by how they connected the representations in the different steps of the interview. On the one hand, it was possible for students to draw upon different ideas as they generated conjectures. On the other hand, the degree to which these conjectures matched a level of normative expert thinking affected how successful they were in seeing the interconnectedness of these representations.

One aspect of representational competence (Kozma and Russell, 1997, 2001) includes the ability to see the interrelatedness of representations across multiple contexts. The data from these four pathways reveals that on the one hand, a students' inability to connect a macroscopic observation with a symbolic equation could be related to a lack of background knowledge about the concepts in question. Yet, on the other hand, students could have difficulty in translating between two representations of the same phenomena. This interview study was less interested in the first category of students, and more interested in those who would appear to have adequate background knowledge, but then still struggle in connecting representations.

Ultimately, conjectures are meaningful in helping students on the pathway to connect and translate across representations. This leads to the conclusion that different **learners with the same evidence can (and will) pursue different pathways towards understanding depending on the conjectures they propose.** However, the success of this pathway depends on the initial ideas proposed as a starting point, as well as the learner's willingness to modify his or her ideas as new evidence is introduced.

2.) Student willingness to conjecture
This type of interview study created a memorable experience that engaged students as they sought to explain a chemical phenomena. Though this particular experimental scenario was unfamiliar to students, they certainly had prior experience with phase and

and color changes. Early steps of the interview set them at ease by asking them to draw what they envisioned at a molecular level, followed by explaining their reasoning.

After a baseline of their ideas was established, it then was possible to further characterize their thinking as conjectures. Indeed, even when students did not appear to understand how to explain the phenomena they were seeing, they were still willing to conjecture. Because the experimental evidence was so tangible (solid disappearing, and colors changing), this elicited a large amount of information from students. Rather than asking students to explain phenomena at a deep conceptual level, they were asked to explain at a level of observation.

This established a scaffoldable and coachable learning environment where students were willing to express and elaborate on their ideas. Even when they expressed apparent discomfort with the chemical concepts involved, they were willing to continue discussing the phenomena they were seeing. However, this did manifest that even college-level learners could struggle with experimental evidence that should have been within their capacity to understand.

3.) Why would usefulness of conjectures vary?
The question arises as to why there would be so many students who could make meaningful conjectures, but then have a fragmented conceptual understanding that would limit their capacity to connect across representations. Are students just merely memorizing information, and struggling to recall it when it is presented in a new context (Clark & Bjork, 2014)? Another response is that background knowledge of students is fragmented, and that they do not connect this information until it has been explicitly demonstrated to them, whether through instruction, experimentation or other means. Thus, every time they hear a new piece of information, they would not know how to organize or connect it meaningfully to information that they already know.

The compartmentalized nature of curriculum in textbooks, and thus its influence on classroom instruction seems to be a culprit. As students are viewing multiple representations of the same experimental phenomena, is there an active metacognitive component in their thinking that is asking why this information does or does not connect? These were all students who had the same exposure to chemistry instruction, and were relatively successful on standard content knowledge assessments. Why would some students find themselves with meaningful conjectures, while others never reached an interconnected understanding?

The first consideration is whether students even have the capacity to link these representations. While it has surely been demonstrated as so, the context certainly plays a decisive role. For example, if they had been primed to see what chapter in the textbook the upcoming material had come from, would they have successfully linked these together? This relates to the consideration of whether students are able to understand representations as explanations of scientific phenomena.

For example, during instruction, it is possible that instructors are using terminology or vocabulary that evokes certain concepts or ideas that students previously associated with other ideas. As a result, when that term is heard by students, it is misinterpreted in its meaning. Perhaps the non-normative vocabulary of students is a culprit. This insight is strengthened from the perspective that chemistry is a language that must be taught and learned. This means that translation issues can result.

An additional perspective is that student motivation may be behind student lack of success. While it was hoped that each student would endeavor to answer the interview questions with their best effort, it was possible that a student would not do so. As a result, their lack of success in the interview format may have been influenced by lack of desire or motivation. Each of the above questions deserves more exploration as possible explanations for why student success varied.

One hypothesis is that the best predictor of success in these interviews was having 1) appropriate background knowledge coupled with 2) conjectures that had a possible hypothesis in mind. While it was possible that a conjecture led to an incorrect hypothesis, students who were leaning towards a more accurate hypothesis were more likely to not need to change their conjectures. More analysis of student background needs to be completed in order to verify and substantiate this conclusion.

Chapter 7: Conclusion, Implications, and Future Directions

Symbols in Chemistry

Chemistry involves using symbols to provide a "sense of the invisible and the untouchable" (Kozma & Russell, 1997). Thus, chemical symbols are the normative language of chemistry, and provide the way for experts to be able to produce, use and communicate. On the other hand, students come to a classroom informed by years of observations and experiences. Their learning is informed by their intuition, conceptions and ideas (Treagust & Chandrasegaran, 2009). The challenge of instruction is to help them see that what they are learning about the behavior of atoms at the submicroscopic level can actually explain their very real experiences.

However, this is hard in every classroom. On the one hand, instructors are constantly make assumptions as to what their students will glean from looking at symbolic representations. On the other hand, there needs to be some accountability placed upon advanced students of chemistry, who have "announced" their interest in learning the material, which should give instructors the liberty to really teach them. These are learners who have already taken several semesters of chemistry, and in many cases, have declared their intention to study chemistry or biology. Yet, even with topics that should be fundamental, students have shaky foundations in decoding symbolic chemical representations if they are not given contextual clues (or cues!)

The norm in college chemistry instruction typically associates more exposure to subject matter with stronger conceptual understanding. Instructors spend the majority of their time presenting symbols for students to learn, and feel justified in doing so, because students, for the most part, are able to learn those symbols. Students encounter a symbolic representation, and then are asked to translate this into another symbolic representation. While not an innate skill, this can be learned (Chittleborough & Treagust, 2007). In a progressive classroom, instructors may be showing the students an atomic-level representation, and asking them to connect this to a symbolic representation.

It turns out that a visualization, whether dynamic like PhET or even a static image in a textbook, can actually describe these two types of representations quite well. Instructors are satisfied if their students look at these visualizations, and then can use chemical equations and words to describe what is occurring. Visualization is a representation or model of something that is taking place. However, while all this teaching and learning is going on, something very significant is being overlooked. What is actually taking place at the molecular level and are students able to "see" this?

Benefits of an Interview Strategy for Student Explanation of Models

De-compartmentalization

There needs to be more instruction that allows students to produce their own explanations of chemical phenomena, which includes generating conjectures to explain their observations. The act of generating and choosing representations becomes much more meaningful when an observable phenomena or context is provided, and when students can refer to chemical models and symbolic representations. This gives learners a greater opportunity to explain what they observed. This interview study revealed that students initially did not understand representations as explanations of the phenomena.

In this study, students were exposed to various phenomena and data that all had a common chemically symbolic way of representing a certain kind of equilibrium. While the chemical symbols remained relatively uniform, the actual macroscopic phenomena and chemical explanations that explained the phenomena actually did vary. This is curious in light of the work of Teichert et al. (2008) who revealed that even if students can correctly represent a molecular-level view from one perspective, in a different context, only minutes later, they would have difficulty doing so. Because of this format, it was possible to elucidate more clearly what the students thought about the same chemical symbols in different contexts.

An interview study as described in this dissertation affords student opportunities to think more deeply about the material presented to them. This tears away at the negative theme of de-compartmentalization, which limits chemistry knowledge (and experiences) to specific domains of learning and instruction. Students' molecular-level ideas depend strongly on the context in which they are introduced, which can have implication for instruction design (Teichert et al, 2008). This kind of instruction can deepen student conceptual understanding by strengthening links between multiple representations of the same phenomena. By examining one chemical concept through several different lenses, it becomes possible for students to have a richer understanding of that concept that extends beyond a more symbolic notation and can be applied in multiple contexts.

Potential Use of Multiple Representations in Classroom Instruction

It is quite crucial that student understanding be at a level where there is evidence of being able to convey this to others. This moves students beyond merely speaking in the symbolic realm, but allows students to teach others. One way to secure evidence of students being able to teach this to others is to have them try to explain this to a learner who may be at a comparable level, such as a classmate or roommate. By taking advantage of their relative similarity in understanding, there can be a strengthening in the conceptual understanding of the student who is being asked to explain. Further work in this area of research will be to examine in finer detail the types of patterns that emerged between the students who had been prepared on a traditional chemistry major track versus those pursuing other career paths in STEM.

It is possible to demonstrate that students successfully use terms such as pH and acidity with a limited understanding of what these actually mean. Symbolic representations need to be linked to macroscopic (properties – color, smell, measurable pH) and atomic views or they do not serve their intended purpose. Nakhleh and Krajcik (1994) pointed out that students are actually not very successful in relating their macroscopic experiences to the models they are studying. If the goal of instruction is merely to understand a model without a view to making this connectable to actual tangible evidence, then students may not even see the relevance of these models to their own observations. Do they even see, much less care, that the symbols that they just wrote out on their exam actually explain why they see a brilliant yellow color in a flame as opposed to just black smoke (or nothing at all)? Chemical models have a focus in explaining things, and should be used to explain the world around them.

Most chemistry instructors (even chemistry departments) are often content with teaching a model behind phenomena and solving equations related to that model (Smith & Metz, 1996). As they help students learn a model, they stop short of giving them the necessary bridge or connection to see how this model connects to a physical, observable, macroscopic reality. One of the biggest lacks in chemistry instruction is the overemphasis on the teaching and learning of models at the expense of student understanding. Instructors unwittingly believe that their job is done if students understand a model. Upon closer examination, students are just being taught a sophisticated way to translate.

The implication of this research is that if students are to be expected to understand chemistry at a conceptual level, as opposed to merely memorizing, there is a strong need to use observations as the starting point for instruction. The analogy to a history class is that instructors are just teaching dates in history, without looking at the causes and motivations for why those events eventually happened on those dates. In chemistry, there is the trap of teaching chemical symbols merely as those dates, without examining the significance and motivation behind using those symbols. To borrow again from history, those who do not learn from it are doomed to repeat it.

Educational Implications

Functionalizing the Triplet Relationship

A goal of this dissertation has been to demonstrate that symbolic representations need to be taught as the powerful links to help connect between the molecular and macroscopic (tangible/measurable) views. Without acknowledging this, students are directed by instructors to focus and spend all their time and energy on studying symbolic representations without realizing their intended purpose as a bridge between the molecular and macroscopic worlds.

The triplet relationship has often been referenced as a way to connect three ways of representing chemical phenomena: 1) macroscopic/observable, 2) symbolic, and 3) sub-microscopic or molecular). Through use of this triplet, chemists have developed a language of symbols to explain observable phenomena by describing or referencing the molecular or atomic world. In the line of others such as Gilbert and Treagust (2009b) and Talanquer (2010), it is proposed that the triplet be reconsidered in its function, especially in the weight given to each corner.

Rather than bearing equal burdens in the teaching and learning of chemistry, the symbolic representation is crucial as a bridge to connect the atomic and macroscopic views. However, without a proper realization of the purpose of the symbolic representation, novice chemistry learners take these symbols as the goal of their instruction, rather than as the models for helping them to understand the connection between the other two corners of the triplet.

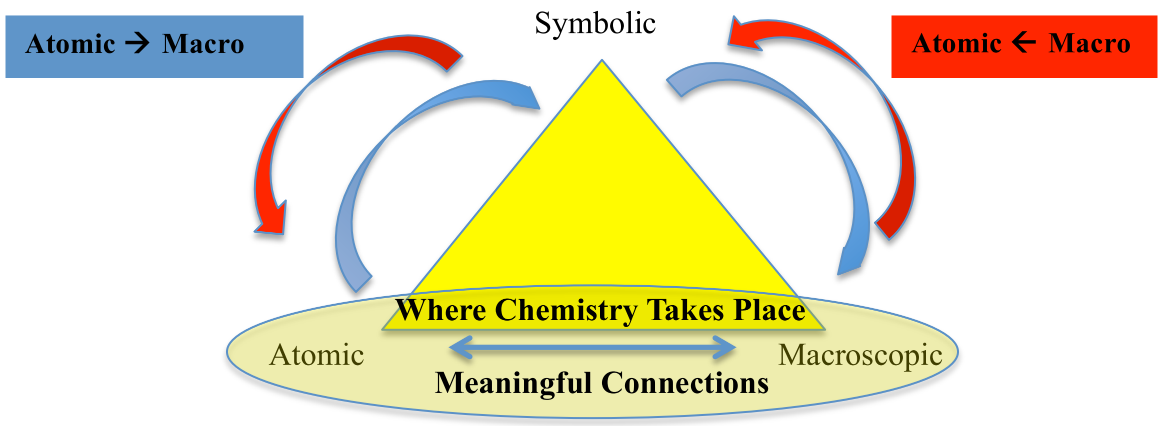


Figure 6: The Triplet Relationship "Functionalized"

While students may come across many types of chemistry representations in their coursework, most instruction focuses on "helping" them to memorize, recall or otherwise commit to memory the symbolic representations. Learners at higher levels who have been more exposed to content and have presumably been given more opportunities to interact with the material will understandably demonstrate better mastery and command over the facts.

Whereas in an ideal situation, the symbols and reactions memorized by a student would translate directly into a visualization and understanding of molecular or atomic behavior, this is not representative of an introductory chemistry course. A student who views an equation on a board could potentially access the content knowledge that then links to explaining why a smell is traveling across the room to their nose.

Ironically, these same students are rarely stopped and questioned regarding their connecting between the symbolic and the other views in chemistry. Rather, they are allowed to persist in their study of chemistry with compartmentalized views of the subject. Even conceptual inventories administered at the graduate school level repeatedly reveal that students face difficulties when translating between various representations (Bodner, 1991). Even future college professors are struggling with reconciling symbolic representations with what is happening at the atomic level. Do freshmen learners stand any chance?

Most students completing their terminal chemistry class do not understand chemistry because they are not being taught to understand symbols in the context of interaction of atoms or observable properties. Instead, they may understand an individual representation when it stands alone, but not when connected or linked to other representations. Since students have difficulty in comprehending the links across multiple representations, there is surely the need to develop instruction that allows for strengthening these links.

Symbolic Representation as a Heuristic

An area of research in a future direction involves examining student's use of the symbolic representations as a heuristic. According to Gigerenzer & Todd (1999), heuristics are a set of "simple rules in the mind's adaptive toolbox for making decisions with realistic mental resources." While expert chemists are able to move through these decisions somewhat rapidly, they also know which conjectures or ideas not to entertain. One governing principle of heuristics is that they are adapted to the environment (or context) in which they operate – thus, they "fit into reality." A second principle involves seeing that different domains of thinking require different specialized mental tools, and some of these need to be "fast and frugal."

Todd & Gigerenzer (2000) include Shanteau pointing out a difference between information used by content experts versus novices. Their claim is that the quantity of information is not connected with expertise, but rather, the capacity to distinguish between relevant and irrelevant cues. Much in the same way that students could be primed by the given equation, experts are more likely to use the cues that are more useful for them to make appropriate decisions. An experienced chemist uses these heuristic of symbolic representations to his or her advantage to move quickly between the macroscopic and atomic views. A novice chemist spends all of his or her time attempting to learn these heuristics, which are ironically not the goal, but merely the shortcut to understanding chemistry (Kozma & Russell, 1997).

Student's ability to classify and rank substances according to physical and chemical properties was explored in the light of this literature on heuristics (Maeyer & Talanquer, 2010). Using this kind of classification to show the relevance of features of different molecules could be used to help students understand common factors when multiple representations are depicted. For example, a certain heuristic would value student ability to recognize similar features between two symbols, and thus translate this information into a corresponding macroscopic property. While students might have some initial difficulty linking the symbolic and the macroscopic, heuristics can be developed to help students develop a more coherent understanding.

However, it's also possible to see that many students rely on isolated features in making decisions about chemical properties, and as a result, could be led astray as they select correct answers for wrong reasons (McClary & Talanquer, 2011). Depending on how a problem was represented, it influenced student ability to make correct predictions related to the physical property of acid strength. For example, the term "weak acid" or the equilibrium arrows in the Given equation were able to cue students to consider HA in a certain way. Thus, there must be a call to develop instructional interventions to help strengthen college chemistry students' abilities to monitor their thinking (think metacognitively) and utilize heuristics. This interview study hopes to answer that call, and open the way for more students to demonstrate their understanding of how representations are connected.

Limitations of the Research

The interview study was designed to expose one student at a time to multiple representations of a symbolic chemical representation. This demanded nearly one hour of dedicated time on task from both the student and interviewer, plus additional time dedicated to processing of audio and written data, and finally, analysis. While the results are useful and insightful, a large-scale implementation would run into severe logistical challenges. Thus, this interview study in its current incarnation would be limited in its effectiveness as an assessment in a classroom.

This research was also limited in that it sampled less than 3% of a given population of students who had completed one semester of college-level general chemistry. While over one thousand fall semester general chemistry students completed an initial survey, less than one quarter expressed a willingness to participate in the interview study. Ultimately, less than 15% of that population was actually interviewed. The population was definitely a convenience-sample, and there was no attempt made to stratify students using any kind of variables. As a result, participants were those who had self-selected into the study, who may not have been representative of chemistry learners in general.

On the other hand, all but 3 of the 33 had earned an A or B as a final grade in their general chemistry class at this highly-selective four year university. It can be argued that these were highly motivated students whose participation in the interview study may be even more valuable because of their willingness to exert "authentic effort" into this process, treating it almost as if it were an actual assessment.

Conclusion

Throughout classroom instruction, students accumulate chemistry content knowledge, without necessarily understanding what is actually happening at the atomic level. If they cannot meaningfully explain what happens with atoms, they cannot provide a strong explanation for macroscopic phenomena. The first necessary step for instructors to remedy this dilemma is 1) to acknowledge that this disconnect is happening and 2) that current chemistry instruction, even at the college level, does not always help to strengthen student conceptual understanding.

We need to be awakened to see the richness that is not conveyed or explored when a standard equation is examined yet again by an uninformed student. We are failing from both the side of recognizing the complexity of the information of what is depicted in a chemical formula, and from the side of not trying to explore more deeply the significance of that representation. Our typical exhortation to students when they look at a chemical equation is to use the chemical symbols to inform some types of calculations.

What if the typical classroom curriculum or syllabus spent a little bit more time giving students opportunities to explain reasons behind real, physical, observable things using atomic-level explanations? With this approach, instructors and researchers might be pointed out as failing to include important details that make it crucial for students to accelerate in developing their chemistry understanding. Perhaps there would be a rush to acknowledge that learning chemistry is much more difficulty than merely teaching students to understand symbols. Look at what is possible when students examine chemical symbols with the desire to understand, and not just as another schema that has to be memorized!

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Appendix A: Official Course Descriptions from UC Berkeley course catalog

(http://schedule.berkeley.edu, accessed Jan 25, 2013)

Chem 1A General Chemistry
Stoichiometry of chemical reactions, quantum mechanical description of atoms, the elements and periodic table, chemical bonding, real and ideal gases, thermochemistry, introduction to thermodynamics and equilibrium, acid-base and solubility equilibria, introduction to oxidation-reduction reactions, introduction to chemical kinetics.

Chem 3A Chemical Structure and Reactivity

Introduction to organic chemical structures, bonding, and chemical reactivity. The organic chemistry of alkanes, alkyl halides, alcohols, alkenes, alkynes, and organometallics.

Chem 4A General Chemistry and Quantitative Analysis
This series is intended for majors in physical and biological sciences and in engineering. It presents the foundation principles of chemistry, including stoichiometry, ideal and real gases, acid-base and solubility equilibria, oxidation-reduction reactions, thermochemistry, entropy, nuclear chemistry and radioactivity, the atoms and elements, the periodic table, quantum theory, chemical bonding, molecular structure, chemical kinetics, and descriptive chemistry. Examples and applications will be drawn from diverse areas of special interest such as atmospheric, environmental, materials, polymer and computational chemistry, and biochemistry. Laboratory emphasizes quantitative work. Equivalent to 1A-1B plus 15 as prerequisite for further courses in chemistry.
emphasizes quantitative work. Equivalent to 1A

Appendix B: Sample Pre/Post-Test Item from Pilot Study

The table below gives information on acid-base indicators. HIn refers to the indicator molecules and In^- to the anion present in aqueous solution. The equation describing what happens when these indicators are dissolved in water is given below.

$$HIn\ (s) + H_2O\ (l) \leftrightarrows H_3O^+\ (aq) + In^-\ (aq)$$

indicator	HIn color	In^- color	K	pH range for color change
methyl orange	red	yellow	3.4×10^{-2}	3.2-4.4
bromocresol green	yellow	blue	2.0×10^{-5}	3.8-5.4
methyl red	yellow	red	7.9×10^{-6}	4.8-6.0
bromothymol blue	yellow	blue	1.0×10^{-7}	6.0-7.6
phenol red	yellow	red	1.3×10^{-8}	6.8-8.4
phenolphthalein	colorless	pink	4.0×10^{-10}	8.2-10.0
alizarin yellow	yellow	lilac	1.0×10^{-11}	10.0-12.0

5) You dissolve 1 drop of phenolphthalein in 1 liter of each of the 5 solutions listed below. Circle all the solutions that will be pink.

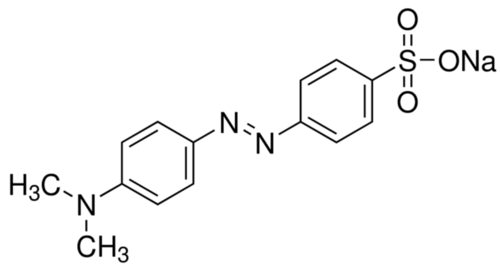
   A) 0.0010 M HCl
   B) 0.000010 M HCl
   C) 0.00000010 M NaOH
   D) 0.00010 M NaOH
   E) 0.010 M NaOH

Write a recipe for turning a pink solution into a solution that is yellow. You may use 1 drop of any indicator and any solution listed in Question 5). Be sure to provide concentrations and amount of solutions.

Provide chemical equations to explain why the color changes.

Appendix C: Source of Reagents in Interview Study

The reagent used for HA was reagent-grade solid methyl orange $C_{14}H_{14}N_3NaO_3S$ (http://www.sigmaaldrich.com/catalog/product/fluka/32624?lang=en&region=US).



(http://en.wikipedia.org/wiki/Methyl_orange, accessed Jan 25, 2013)

A small vial of solid methyl orange powder was displayed for students. As evidenced by the photographs, the colors of HA are described as below.

Images of colors:
HA and H_3O^+

During the experiment, aqueous HA was generated by placing a small grain of methyl orange into distilled water, and then diluting it further as described in Appendix D. An acidic solution consisting of 0.06M HCl was used as a source of H^+ for a later step of the interview.

A special thanks to Karen Chan in the Chemistry Demonstration stockroom for supplying the reagent.

Appendix D: Interview Study

Goal: Have student elucidate their thinking by drawing and explaining. Expose difficulty in understanding equilibrium expression. Reveal usefulness of symbolic equation in connecting between atomic and macro views.

Step	Data – Evidence	Protocol (Questions) – Initial Prompts	Follow-Up Questions
#1 SYMBOLIC Representation - Show student a standard equation	$HA + H_2O \leftrightarrow A^- + H_3O^+$	This is a statement that you've seen projected on a screen, on a blackboard, on your computer or even in a textbook. -What does this mean to you? -What does this symbol (equilibrium) mean? -What physical properties, such as color, temperature or phases would you expect? -What additional information do you need from me to make sense of this?	Goal – elicit thinking on the atomic level -establish a baseline of student's conceptual understanding of acid/base Anticipate K_a discussion (stay away from solving math) -What about concentration is relevant here? Why did you bring it up?
#2 Transition to ATOMIC view	Blank paper	Now imagine you can zoom in on this statement so that you could see individual atoms. Draw for me what this statement looks like in the following 4 scenarios. 1.) Draw before (or, the moment when they're combined) 2.) Draw the slight before 3.) Draw the slight after 4.) Draw what it looks like over time?	Attempt to find out what they know by questioning their drawing. -Elucidate what "before the reaction" means in the students conception -"After the reaction" has occurred EVEN IF THEY'VE DRAWN IT CORRECTLY – ask what they mean

#3 MACRO Representation -Identify physical properties of an indicator (methyl orange)	1.) Show them a sample of methyl orange (solid and orangish-red) 2.) Put small grain into 50 mL water 3.) Add water to bring volume of solution to 120 mL.	Here is a vial. The contents of this vial can be described as HA, a weak acid. 1.) Describe what you see. 2.) Predict what will happen when you put one grain of this in 50 mL water. What color? What phases? -What do you expect to see in solution? 3) Put small grain into 120 mL water 4.) Observe the dissolved indicator.	If red? If clear, If orange, why? -Anticipate questions about dilution How do we know this is not just diluted?
#4 MACRO to ATOMIC link	What occurs on the ATOMIC level to explain the colors we saw?	Copy down the initial statement onto the top of paper #2. 1.) Describe what you expect to see. 2.) Rank the species in terms of the greatest amount of each species present. 3.) Under each species, list its contribution to color. What color does each species contribute? Draw for me what this looks like if you can see the individual atoms. What will happen if I add 100 mL of water? What will I expect to see? Solids?Colors?	Based on what you have in your beaker, how does the statement describe what you see?
#5 EXPERIMENT-Experiment to expose thinking about equilibrium	Add concentrated H+ in the form of one drop of 0.6 M HCl	Now, we will add a source of H+. The only species contributed to our statement is H+ (any other species present do not react.) I will add less than 1mL of H+. 1.) What is your prediction concerning what you will see? What else could you see?	Issues: Aqueous Dynamic Endpoint Reversability LeChatelier's Principle Why draw it that way?

		2.) Does this match your expectations or it is surprising? Draw: What is happening on the MACRO level? What is happening on the ATOMIC level? Generate a(n) equation(s) to describe the process you just witnessed. Are there more than one taking place?	Le Chatelier's Principle –what does that mean on the MICRO level? Why would it shift? – dynamics? Do they stay together/react forever? Dynamic view is not relevant when equilibrium is first established. Compensate for addition of H+ More A- with H+ collisions Completion? What color is produced?
#6 ATOMIC to MACRO link	PHeT Visual -Slider transition from Yellow to Red	Notice the statement we have been working with and the statement on the visual are the same. Describe to me what you see when you move the slider on the visualization. 1.) Move the slider to show me where the solution resulting from HA powder and H2O is. Why this point? 2.) Move the slider to show me where the solution resulting from adding H+ is. Why this point? Why not further to the left? Where does the visual deviate? Do you want to see the water? Is it helpful or confusing? Do you want to keep the water? What does the visual connect for you?	Write an equation that describes what you saw in the experiment. If I had a 1 Liter beaker of 1M HA in front of us, describe what you would see. If we were standing in front of a swimming pool of 1M HA, what would you see?

#7 CHALLENGE	How would you make an orange-yellow solution?	What would one need to do to make an orange solution?	Equal amounts of HA and A-

$$HIn (s) + H_2O (l) \leftrightarrows H_3O^+ (aq) + In^- (aq)$$

indicator	HIn color	In- color	K	pH range for color change
methyl orange	red	yellow	3.4×10^{-2}	3.2-4.4

Appendix E: Modes of Student Thinking During Step II Drawing Task

Student number	Code	Comments	Identity of HA
4B2	ATOMIC	Retains same model of drawing throughout. Uses transition states to indicate formation of bonds.	Ions
4B3	ATOMIC	Retains same model of drawing throughout Uses partial bonds to indicate the formation of H_3O^+ and A^-	Ions
4B4	ATOMIC	Drawings progress into a more multi-representation Uses partial bonds to indicate the formation of H_3O^+ and A^-	(l) or (s)
4B5	SYM	Uses H^+A^- to represents HA Drawings progress into a multi-representation Uses arrow pushing to indicate the formation of bonds	Ions
4B6	SYM	Uses charges to represent HA Uses partial bonds to indicate the formation of H_3O^+ and A^-	Ions
4B7	(MISC) ATOMIC&SYM	Progression in thought (Lewis Dot Structure→molecular→symbolic→atomic) Uses dipoles but doesn't indicate the breakage or formation of any bonds	Ions
4B8	MOL	Retains multi molecular representation throughout drawings. Uses partial bonds to show formation of H_3O^+ and A^-	(l)
4B9	ATOMIC	Progresses to a multi representation of molecules Uses partial bonds for breaking/forming bonds	(aq)
4B10	MOL	Uses symbols in drawings, square represents H_2O and circle represents HA No indication of bonds breaking or forming	(aq)
4B11	MOL	Uses symbols in drawings, square represents A, circle represents H and triangle represents O No indication of bonds breaking or forming	(aq)
4B12	SYM	Retains same model of drawing throughout Uses partial bonds for breaking/forming bonds	(aq) or (l)
4B13	SYM	Retains same model of drawing throughout Uses charges to represent HA Uses donation of electron pair to represent formation of H_3O^+ and A^-	(aq)
4B14	SYM	Uses a plus sign in initial representation and	(l)

		charges on HA Retains same model of drawing throughout	
4B15	ATOMIC	Uses charges to represent HA Progresses to a multi representation of the reaction Uses dipoles and arrow pushing to represent formation of H_3O^+ and A^-	(aq)
4B16	MOL	Uses symbols in drawings, circle represents H, square represents A and triangle represents O No indication of bonds breaking or forming	(aq)
4B17	MOL	Presence of all four molecules in initial drawing No progression in drawing they all remain the same Uses partial bonds and dipoles to represent formation of bonds in drawing 2	(l)
4B18	ATOMIC	Retains same model of drawing throughout Uses partial bonds and dipoles to show formation of H_3O^+ and A^-	(s) or (l)
4B19	SYM	Drawing 1 is represented by a beaker of water and HA outside. Progresses into a multi representation of the reaction	(aq)
4B20	MOL	Retains multi-molecular view throughout	(aq)
4B21	MOL	Presence of all four molecules in initial drawing Retains same model of drawing throughout Uses partial bonds and dipoles	(l)
4B22	MOL	Molecular representation with motion, retains same model of drawing throughout Uses partial bonds and dipoles to show formation of bonds	(aq)
4B23	MOL	Retains same model of drawing throughout Uses partial bonds and dipoles to show formation of bonds	(aq)
4B24	ATOMIC	Progression of thought from atomic → molecular representation Uses partial bonds and dipoles to show formation of bonds	(aq) or (s)
4B25	MOL	Retains same model of drawing throughout Uses transition with arrows to show formation of bonds	(aq)
4B26	MOL	Retains same model of drawing throughout	(aq)
4B28	SYM	No progression in thought, retains same model of drawing throughout No reactants present in Drawing 4	(l) or (s)

4B29	MOL	Begins with presence of partial bonds between H from HA and O from H_2O Leads to 3 different scenarios for drawing 4: Weak acid does not form any products, simply HA and H_2O. Okay acid forms both products and reactants. Strong acid forms only products	(l)
4B30	MOL	Retains same model of drawing throughout Donation of electron pairs form water to HA leading to partial bonds and dipoles Only products present in drawing 4	(s)
4B31	MOL	Drawing 1 is represented by a beaker of water and HA outside in a multi representation Uses partial bonds to indicate formation of products	(aq)
4B32	MOL	Drawing 1 is represented by a beaker of water and HA outside in a multi representation	(s) or (l)
4B33	MISC (ATOMIC&SYM)	Uses symbolic equation with space filling rep beneath it Also uses a teeter-totter figure to show balance between reactants and products Uses partial bonds and dipoles to show formation of products	(aq)

Appendix F: Anticipated Conjectures

	Hypothesis	Possible Conjectures
1	Students will focus on the symbolic equation.	- Attempt to correlate two sides of one equation with one flask - Dynamic Equilibrium - Math Equation - Ratio - Phase – precipitate/gas/aqueous/liquid - Quantity - Heat/Energy Evolved/Needed - Intermediates - Excess Reagents - Speed of particles - Net ionic equation - Stoichiometry of equation - Balanced - Enthalpy - Dynamics of Reaction - Equilibrium Value (K) - Reversability
2	Students focus on calculating [H+], pH or K_a	- seen as a ratio - not seen as a ratio - seen as an absolute number - seen as bounded by 0-14 - not dependent on acid strength - not dependent on concentration - seen as an absolute concentration
3	Students focus on and attempt to explain color	- shades of color - relative quantities - mixing - dilution vs. reaction - equivalence point - color/numbers – characteristic of absolute concentration - ratio of $[H^+]$ to water – may be overlooked - color of pH paper correlated to 0-14 - Indicator present
4	Students will focus on water molecules in a dynamic visualization	- amount of water present - students ignore water molecules and assume water solubility - pay attention to H^+ concentration instead - confusion about H_3O^+ versus H^+ - Recognizing that the water molecules "go away"
5	Students will seek out macroscopic properties	- Solubility - Relative Amounts (size of container) - Phase - Temperature - Color - Smell

		- Speed of reaction - Turbidity - Gas/Precipitate Present
6	Students will seek to evaluate concentrations	- Indicator- tendency to break apart (K) - If $[H^+]$ is fixed, to keep it constant, In- and HIn also have to be modified to keep Ka the same - If H+ goes up, then In^-/HIn has to go down for Ka to stay the same - As H+ changes, the ratio changes - Turning point, when pH = pKa - What is the connection that H+ concentration affects the equilibrium? - Given Ka, what is the major species in the solution?

Appendix G: Student 4B17 Interview Transcript

P: Good morning my name is Paul Daubenmire, I'm a researcher with Professor Angy Stacy in the College of Chemistry. We are looking at students' conceptual understanding in chemistry and how learning about student ideas can help us to develop better curriculum.

So this morning what we are doing is called a think aloud interview, and basically I'll be presenting you with some data and I'd like you to just think aloud what you are thinking. So that means you can speak it, you can write it, if its equations, drawings, or anything like that. And also if there is something that doesn't make sense, say why it doesn't make sense, if there is a conflict and you are balancing between 2 options, give me both options. So there are not right answers I'm looking for; instead I'd like to find out more about how students are thinking about the data that is presented.

The first question involves this<> statement here. You've seen it on a blackboard, you've seen it on a projector, textbook, on the internet. In your own words, what does this<>mean to you?

S: (2:00) Well, there is the double arrow in the middle and that is equilibrium. And I want to say that this is an acid-base reaction.~ or like, yeah, acid base. On the left here we have HA, an acid, which gets de-protonated, or like, it loses the H and donates it to the H2O, so that becomes H3O+ and this is A-. And the process also reverses, it goes both ways.

P: Good. I noticed right away you started with that  , say more about that particular symbol.

S: (2:39) Okay, like I mentioned, the reaction goes forward and backwards, it is dynamic, so usually there would be a K here that tells you the extent of the reaction in a given direction. So which side is more favored. The fact that it is a double arrow instead of just one direction means that it goes both ways, like to a significant amount.

P: So what could you maybe give a hypothesis about any characteristics of this<> HA?

S: (3:16) So if it is a strong acid, it will dissociate easily, it will lose its proton easily. It wants to donate the proton to the H2O. So that means it will go forward more, so the K, which is products <u>of</u> reactants, K will be bigger, since the numerator will be greater than the denominator. If it is a weak acid, it will dissociate less, the K will be smaller.

P: (3:42) What could you say about the properties, such as temperature, color, or phase of these, we'll call them "species," in this $HA_{(s)} + H_2O \rightleftharpoons H_3O^{\oplus} + A^{\ominus}$ statement?

S: Temperature \ I'm not sure about temperature. Color, if you had an indicator in there. Indicators sort of work like this, I remember, I'm trying to think back. So the extent to which this (HA) species dissociates will be a certain color. Let's say if it's completely dissociated, if it's A-, that could be red. Whereas if it's, where am I going with this, whereas the other extreme, which is here* would be blue. So, if it dissociates partially, it'll be somewhere in the middle, which is purple. So, judging by the color, you could maybe tell how strong or weak the acid is.

P: (4:42) Interesting. What could you say about—just to establish—the colors of these two (H2O, H3O+)?

S: H2O is clear, water. But when it is in solution with these two(HA, H2O), or with the acid as well, I guess if you had an indicator in there, it would be the color of the acid.

P: Okay, again, let's treat it, I noticed you brought in an indicator, let's treat it as if it's just this $HA_{(s)} + H_2O \rightleftharpoons H_3O^{\oplus} + A^{\ominus}$.

S: Just that-I would say there is no color change.

P: (5:15) Let's revisit this idea of phases. What could you say about the phases that are present with each of those $HA_{(s)} + H_2O \rightleftharpoons H_3O^{\oplus} + A^{\ominus}$ species?

S: Water would be liquid. These (H3O+, A-) are both ions, so they would be liquid as well. The whole thing would be in a solution. I'm thinking that HA could be a liquid, or it could be, yeah, I'm going to say it is a liquid.

P: Okay, so liquid(HA), liquid(H2O), and then—

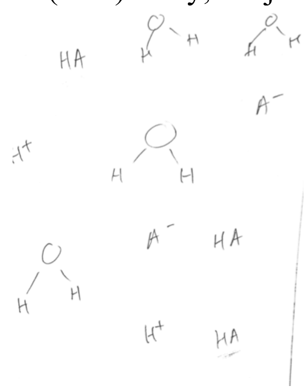
S: —this(HA) could be a solid, if you put it in H2O it would dissolve, and then, it would be, the ion transfer <u>liquor</u> (5:48).

P: (5:49) So then part 2, we are going to take this<> statement and zoom into the atomic level. And I'll have you draw for me 4 different scenarios. The first scenario is before this<> happens, what does it look like? So you zoom into the atomic level, you could see the individual atoms. In box 1, before it happens, what does it look like?

S: (6:18) So this, the white part will be—

P: —and you can define it however you—if you need to draw a beaker or a box.

S: (6:26) Okay, I'll just say the box is the beaker. (student drawing/writing



and begins to describe what she is drawing) So water there and then the acid which is not dissociated yet will just be over here<>, and then multiple particles floating around. And then some of this will have dissociated as well, like that. Maybe some more water. Yeah, like that.

P: (7:00) So if I, I'll tell you that this is a weak acid. HA. What does that, does that cause you to revise anything in your drawing?

S: There will be more HAs together and fewer of the H+ and A-.

P: So more HAs. So let's move forward a split second in time, from before the reaction, to slightly before. So slightly before the reaction, what does it look like, in 2?

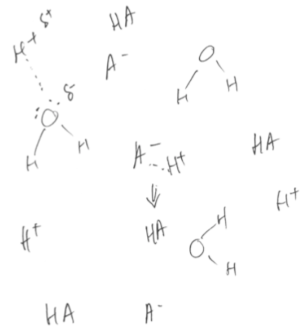
S: (7:42) \\ slightly before the reaction. Umm, so this (referring to box 1) is before anything happens? And the reaction being that H would go to protonated water. Is there any betweens? Is there stuff in between?

P: If there were stuff in between, what would it look like?

S: \\ I guess more dissociation on the part of HA. That's all I can think of. So, still some HA. Is this still a weak acid?

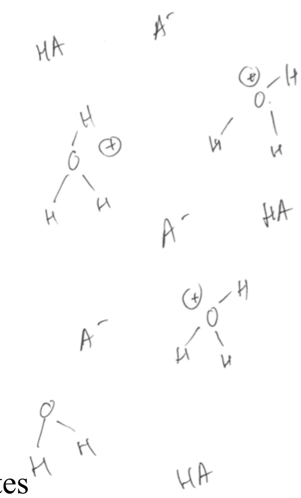
P: Still a weak acid.

S: Yeah, more dissociation is what I would say.



(draws/writes)

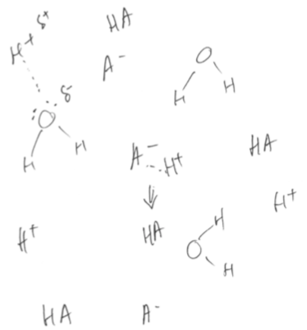
P: (8:53) Then let's say slightly after the reaction, so a split microsecond after 2 is number 3. What does that look like?



S: (student draws/writes) So the hydrogens have been donated to the water. So we have hydronium ions with a positive charge. And then we have the A- species sort of floating around. And then we still have some undissociated HA. And then also some not yet protonated waters.

P: So in that split second between 2 and 3, is there anything that happens in terms of the position, or the alignment of your molecules?

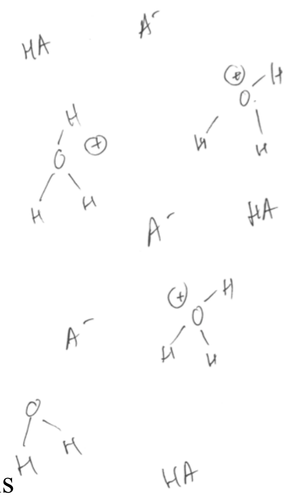
S: (9:58) Oh, umm, yeah, so the water this side—one side being with the electrons and the other side with the hydrogens—the electrons side would align towards the H+, and this is like negative, and this one, well, with a positive charge. So there is like a bond forming there, I guess. And so, all of them align that way just because of the charges. And then, they form here, a bond.



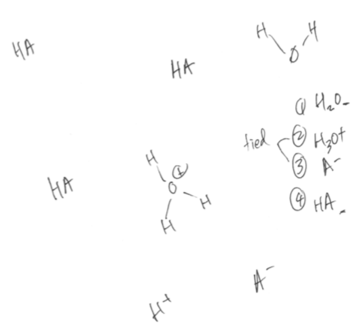
P: (10:30) What about this A-?

S: Yeah, some of it could dissoc—could re-join with some H+. So some of that would make more HA (writes on the paper). So I guess it is a dynamic process. So the ions don't just dissociate and just stay ions. Some of it reforms.

P: Good, so you are referring back to the dynamic process. So we've been taking these little microsteps. In drawing 4, let's say a day passes, or a long period of time. What does this statement look like after that?



S: (11:08) About the same as this. There is still that dynamic process going on, but I don't know what K is, but if it is a weak acid, I'm assuming that a number of the HA species is still together and not protonating in water yet.



(student writing/drawing) At the same time we do have protonated waters still. And then we do have unprotonated waters as well. And also A- and H+.

P: So you had to go through and rank these $HA_{(s)} + H_2O \rightleftharpoons H_3O^{\oplus} + A^{\ominus}$, 1 being the largest amount present, and 1 down to 4, go ahead and rank these in terms of amount present.

S: Okay, \\ (thinking) I would say (student writing), are we starting with equal amounts of HA and H2O?

P: (12:20) Let's say are starting with the most H2O.

S: I would say H2O is still the most. H3O+ and A-, those are the same right? So can I say these are tied?

P: Sure.

S: And then the least, maybe HA. I know these two<> are the same, and I know these<> are probably different amounts. I want to say—I don't like putting HA at the bottom because I want to say there is still more HA that's still not disassociated

① H_2O
tied ② H_3O^+
③ A^-
④ HA

yet, but relative to the other species, then HA would be the least.

P: And by saying there is more HA not dissociated yet, what are you conceiving?

S: (13:10) That it's a weak acid, that it doesn't want to donate the H+ as much as a strong acid would.

P: Slide that piece of paper forward, and on page 2 on the top, copy this equation over, and I'll prep a couple things.

(P places a vial on the table) Describe for me what you see in this vial.

S: (13:42) A reddish-orange solid.

P: And what would you expect or what are some possibilities, not knowing its identity, of what could happen when you put it in water?

S: (13:55) Do I stir it or no? After I put it in do I stir it? Is it mixed?

P: Good. Let's walk through that.

S: If there is just water in the beaker and you just pour this in, a lot of it would just float. Just because it's a light powder.

P: I should rephrase it – we are going to be putting a grain in.

S: (14:22) Oh, a grain.

P: Right, not the whole vile, but just 1 grain. And I'll even demonstrate about how much we are going to be putting in (takes a small grain out and puts it into an empty glass beaker). So about like that.

S: \\ (thinking) And then we are adding the water in? It could dissolve. After you put the water it, then maybe the water is swirling around, and then we wouldn't see the red solid as it is. It could not dissolve. We could see red particles just floating around in the water.

P: (15:08) If it does dissolve, what would we expect to see? What color would we expect to see?

S: Probably clear, just like the water. I mean I don't know how much the color of the solid would affect the solution, but just judging the amount that we are putting in, I would say not too much. It will probably stay clear.

P: So I'll tell you, it is soluble. And so, based off of that, then your prediction would be that you wouldn't see any more solid. And then, you'd say probably remain clear because of the small amount.

S: Yeah.

P: (15:56) Let's go ahead and I'm going to add about 50 mls of water, and describe to me what you see. Oh yeah, and you mentioned something to me about mixing and stirring. What was your thought there?

S: \\ I was thinking like paints, like powdered paints, when you put them in like this and you add water, you get this water color kind of color. So I wasn't sure if it was that kind of thing, or a salt, will it just dissolve and it'll stay clear. I was thinking of a color, but—

P: —So I'll tell you, this is actually a weak acid. This is HA.

S: Mixing would make the dissociation, the dissolving occur faster. If you don't mix it, it would just sort of sit there, remain as a lump. The size would decrease, but it would have a hard time dissociating.

P: Anything else not knowing the identity?

S: (17:04) No, I don’t think so.

P: Okay, let’s give it a shot them. We’ll add 50 mls of water. Let me know what you are observing.

S: Oh (seems surprised). The color—I see light yellow liquid. A little bit orangey. So when you added the water, it’s still kind of there, yeah (picks up the beaker to examine more closely). Yeah, I can definitely still see grains, but surrounding each grain is where the yellow is coming from. So obviously that is the source of the color. Is it cool if I mix it?

P: Yeah, absolutely. (Hands S a stirrer)

S: (17:50; S stirs) So mixing it, I am seeing fewer and fewer red grains and the color is deepening.

P: So looking at this (the beaker with solution) back to our equation $HA_{(s)} + H_2O \rightleftharpoons H_3O^{\oplus} + A^{\ominus}$, where would you attribute, what color would you attribute to each of those<> species, seeing what you are seeing with our flask?

S: So this(HA) is a solid, so I would say this(HA) is red, red-orange. The water is clear. H3O+? Hmm, hard to say. Do ions have color? And this(A-) I would say is what’s sort of yellow. Yeah. Not sure about that(H3O+) one.

$$HA_{(s)} + H_2O \rightleftharpoons H_3O^{\oplus} + A^{\ominus}$$

red/orange clear clear yellow

P: Okay, maybe as a hint, think about the auto-ionization of water. What is going on there?

S: (18:54) \\ Oh, so from water to water? Transferring protons, I guess. It would still be clear.

P: Yeah, because that’s happening right there (holding up the bottle with just water in it). So you could say that is clear. What would you say then about this yellow beaker, and the relative amounts. Again, ranking 1 through 4, and you could write those numbers there.

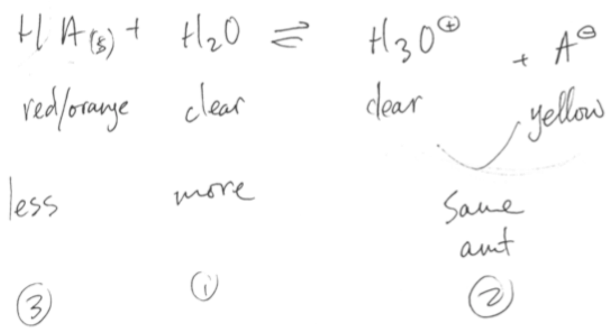
S: \\ So I think it’s pretty clear that the predominant color here is yellow, but there is still some red-orange. You could still see the grains here, so that’s still present, but in a small amount. So I change my mind about these two(H3O+, A-) being equal, because I didn’t think about the autoionization of water. Yeah, I just thought that whatever, however much H+ comes off, that’s how much is going in there(H3O+).

P: (20:03) For simplicity, let’s leave the autoionization off.

S: Yeah, then I would say that these two(H3O+, A-) are still the same amount. And then this(HA) is less, and this(H2O) is more.

P: Less, compared to each other? Again, using a 1, 2, 3 now, how would you write it?

S: (20:32; student writing) Maybe this<> would be 1 and this<> would be 2.



P: So there is a possibility that the water could be 2 and the products—

S: —actually, no, because the amount that this dissociates, controls the amount of these two, so I’m going to stick with 3, 1, 2<>.

P: (21:00) And then what do you think would happen now if we add more water to what we have there (the beaker with yellow solution)

S: (student picks up the beaker and stirs it around again as she observes)

P: Are the little grains still there?

S: (21:14) Yeah, there are still a couple of them, I’m taking care of those. Well, let’s see. Well, part of me wants to say it would dilute the color, because you are adding more clear. But at the same time if you are adding more water, you push the reaction this way (motioning towards the right), so more yellow would come out too. I’m not sure. Can I?

P: Go for it. (referring to, go ahead and add more water)

S: (student adds more water slowly, almost doubling the amount of liquid in the beaker, then observes) Okay. It’s kind of hard to tell, but I think it diluted a little bit the color.

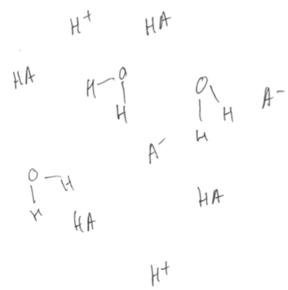
P: (21:54) So let's actually do this. Let's take a sample out and let's add even more. (P pours some from the beaker to an empty beaker)

S: (student adds more water to the original beaker of yellow liquid) Yeah, definitely less yellow.

P: So that is one of your hypothesis?

S: Yes.

P: (22:14) Adding more water made the solution the same color, but less yellow. Can you draw for me, and again zoom down to the atomic level, what you see in this<> beaker (referring to the now very diluted yellow liquid)?



S: (student writing/drawing) So, more water, obviously. Still the same amount of HA. Well, since we split it (referring to pouring the solution into 2 beakers)

P: Let's do that. (P pours the 2nd liquid back into the original beaker, so now all the solution is in 1 beaker) We'll make that easier.

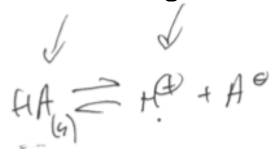
S: So still the same number of HA molecules. Because we didn't add more or take any out. We just added more water, so that's the only thing that should really be changing. Still some H+ and still some A-.

P: (23:19) Okay, so your rankings?

S: The rankings for this one (referring to yellow liquid beaker)? H2O by far, number 1. I'm still going to say the same thing actually.

P: So now we are going to introduce a source of H+. And basically any other species in there are unreactive, won't affect our statement

here . So there only thing here is that H+ would be added. What would be your prediction or predictions, possibilities, of what we would see in our beaker?

S: (24:01) \ More H+, hmm, well, what I'm thinking is if we rewrote this without writing in water, (S writing on paper ) we would just have a dissociation. So if we increase H+ then this(A-) would increase as well.

P: So say this again—if you increase H+ and you would see HA increase?

S: Right, you would push the reaction to the left. So you would see more HA, so it's tempting for me to say that we would see some red grains maybe reform.

P: (24:42) And you don't seem—you're not convinced. Any other, shot in the dark, any other possibilities that you might see?

S: \\

P: So let's pursue that a little, if the red grains do appear, what color is the liquid?

S: It becomes less yellow.

P: (25:09) Less yellow. Okay. So red grains appear, less yellow.

S: Red grains may or may not appear. I'm not sure.

P: If the red grains don't appear, what color would you say this is?

S: Still less yellow.

P: (25:25) Any other possibilities?

S: The beaker would overflow?

P: Okay, let's do this. We are going to be adding less than a milliliter. Maybe half a ml. So it's not going to overflow. And again, your observations.

S: (25:49) (student leans forward to observe and consider) \\

P: (drops the solid into the solution) And you could stir it if you want.

S: (student stirs) It's not quite red. Okay, that makes sense, actually.

P: Okay, what makes sense?

S: (26:17) The grains probably wouldn't reform to the extent that I could see them, but the solution would change color, back to red-orange, right? So it's sort of like a balance between colors. When we had more A- it was more yellow, then we added H+, so it pushed it this (to the left) way, so now it should be more orange.

P: Okay, so, you're happy with what you see?

S: Yeah, it works.

P: (26:47) So let's, we'll revisit that shortly. We're going to take a look at a visualization here. And, it has our familiar statement, as well, as you can see here, there is a slider bar, it goes back and forth. And we have the waters depicted. I'm going to hide the waters. Take a look at this and tell me what you are thinking as you look, and you can move the slider back and forth.

S: What's the slider?

P: Good question. See if you could find out what—tell me what the slider does.

S: (27:29; student working with visualization) The slider could be, the slider could be the extent of the reaction, or how much time you are giving it, I guess. So we're starting with HA, a lot of HA, and then H2O, obviously, which isn't there, but, and then a little bit of A-, a little bit of H3O+.

P: What's that about?

S: So that means some of the HA has dissociated. And some of the water has been protonated, but it's just starting, maybe~. And then as we keep going we are getting more and more of the products and less of the reactants. And then at the final stage here, on the far right, we have mostly A- and H3O+. And then very few HA that have not dissociated in protonated water.

P: (28:47) What does this*, this is the same equation, the same statement. What does this tell you about what is happening in the visualization?

S: Right now, with this visual?

P: Yeah. You notice the statement here does give you these*—

S: (29:09) —Right, it tells you I'll need, for a lack of a better word, "ingredients"—

P: We'll use "species."

S: Yeah, all the species that are in the beaker, it tells you how they are related, I guess. So when you—the relative amounts, maybe? Uh, that's totally wrong. So let's say over here on the far left (working with visualization) we see a lot of HA, a lot of H2O, very little A- and very little H3O+. So like, the products form together and the reactants sort of disappear together.

P: What do the colors tell you?

S: (29:49) It's exactly this (pointing to the beaker with the solution that you've been working with). So HA is the red-orange, and then H2O and the H3O+ are both clear. Well, there is a little bit of a distinction so you can tell them apart. And then A- is the yellow. So here at the beginning of the reaction we had mostly red. As we added water, as the reaction proceeded we had more yellow species and then that's why the solution turned yellow. And then when we added H+ again it went back.

P: (30:29) So where would you put this (pink sln), if you had to put that on the slider scale, where would you—

S: Not completely to the left, but closer to the left than to the right.

P: So you have it maybe about 1/3 over?

S: Yeah.

P: Okay. Anything that this visual doesn't show you about the experiment that we did?

S: (31:01) I wish I could see some movement.

P: Good. What kind of movement would you want to see?

S: Just them floating around, mingling, I guess. This is a pretty good visual because it shows you everything in a random place. You know, like you don't see all the yellows in this group, in this corner. So that's good. But if we could see some of the movement and the ions sort of bumping into each other, or something like that. Or maybe the alignment of the water with the H+, that would be helpful.

P: (31:36) Considering our statement again (referring to the original statement) and the work you've done here*, how does this visual match our beaker? Or not match?

S: Well, what you see, you don't see individual red specks and then yellow specks. You see them combined. So like I was seeing earlier with the indicator, you don't see just red or just blue. It's sort of like in the middle. So that's what I would say here. We don't see just yellow and just red. We see an orange color cause it's somewhere in the middle.

P: (32:19) What about our solid (picking up the vile of solid)?

S: I don't think we really got to see this* (referring to something on visualization). Just because as soon as, I don't want to say as soon as. This (referring to visual) was for a very brief time. When we poured the water—

P: So the far left, we are looking at here.

S: Yeah.

P: When you put water in with the solid—

S: You could see the red streaks and then all of the sudden it turned yellow. It occurred really quickly.

P: (32:56) So if we are looking at this statement (the very first statement) to represent what we did in our experiment today, is there anything you'd want to add or modify on this statement to make it more representative of what we did?

S: \\ You could write sort of like accompanying reactions, like this, $HA_{(s)} \rightleftharpoons H^{\oplus} + A^{\ominus}$ and also H2O.

P: Okay, so let's revisit this<> one. What is that<> telling us?

S: (33:32) So this is just strictly the dissociation, the HA. Not with it mingling with water, just with HA.

P: So the HA just dissociating.

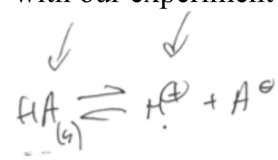
S: Yeah, without regarding water.

P: And what are the phases there, that you put on there?

S: I would say they are all in solution, so all aqueous.

P: So how does this $HA_{(s)} \rightleftharpoons H^{\oplus} + A^{\ominus}$ equation with all aqueous—aqueous HA, equilibrium symbol, H+ aqueous, A- aqueous, relate to your equation up here*?

S: (34:09) Actually this(HA) could be solid, I think. Yeah. When we write the dissociation of salt, we start with a solid, and then it is aqueous on the other side, and water is just implied. So I think it is just like half of this $HA_{(s)} + H_2O \rightleftharpoons H_3O^{\oplus} + A^{\ominus}$ whole equation. And then the other half would be water.

P: So let's take your roommate, who is a beginning chemistry student, and things like this (original equation) don't come intuitively, not enough experience, how would you take this statement and convey what we saw with our experiment? Either through this statement, or adding on like you did here  ?

S: (34:51) I would start out with a different species, making sure she understands, like HA is our solid and then these(H3O+, A-) are ions, and this is water. So start with that. I don't know how beginning she is. But that's important. I think the color balance really makes sense to me. I would maybe use an example that has a more obvious, like red, orange, and yellow are all next to each other on the spectrum. So I would use something more dramatic like red to blue, and then purple is an obvious in between. Yeah, I think by labeling it like this* and with the equilibrium, seeing the color change makes sense here. So if it's more red, we know there is more of this(HA) species. If it's yellow we know it's more of this(A-) species. That makes sense to me. That really helps me. And then from there on I would go and draw these* pictures. I wouldn't start off with this*. I would start off with, what do you see? How could you relate it to the equation? And then go into the molecular level.

P: (35:55) So then the final challenge, and I'll bring back 2 samples. If we had this(yellow sln) which is approximately where our A- was, and this(pink sln) sample, how would we create something in the middle?

S: \\

P: And again, this(yellow sln) was just created by adding water and the solid HA and this(pink sln).

S: Do I have to use both of them?

P: You just have to create something in the middle.

S: Okay, I would do what we just did, add water to the red solid. And that would make something like this (pointing to the first sample of A-). And then I would add H+, but not so much that it turns this (referring to the second sample) color. So like we maybe added 10 drops here(pink sln), I would add 5.

P: (36:55) How would you know you're exactly in the middle?

S: I think then you have to do some calculations. Judging by the color, maybe you could eyeball it. It may be tricky with these colors. Well, let's say this is like our starting state (referring to the first sample of A-). If we added a certain number of drops of H+, I think that maybe we could divide that by 2~? I'm not sure if that would work exactly. So I guess a ten here* and a five would be what is in the middle.

P: (37:28) Okay, so let's think back to this visual here. If this* is the extreme, and I think you said about 1/3, that was about where this(pink sln) was, where would you put the color?

S: Right in between there. Maybe at the 2/3 mark.

P: So you take the all yellow species, and then basically about half way between this orangish-reddish solution and the yellow?

S: Right.

P: Okay. So we'll stop there.