Student Conceptions of Ionic Compounds in Solution and the Influences of Sociochemical Norms on Individual Learning

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Prof. Gillian H. Roehrig

May, 2013

Acknowledgements

A work of this magnitude can never be done in vacuum. I am indebted to many individuals who I am very grateful for all their time and support through the years. Without doubt my advisor, Prof. Gillian Roehrig, stands out as the most deserving of my thanking. Gill was more than an advisor, she was a mentor and advisor all wrapped into one. In her advisor-mentor role, she molded my thinking, taught me how to ask the right questions, listened attentively to my own ideas with respect and interest and, above all, ensured I had the support I needed to successfully complete this work. I could not have asked for a better advisor and mentor!

I am also indebted to the members of my dissertation committee: Prof. Bhaskar Upadhyay, Prof. Fred Finley, and Prof. Frances Lawrenz. Prof. Upadhyay has always brought issues of culture and the role of science and social justice to my attention. I have tremendously benefitted his knowledge in this area and look forward to dialogue with him about these issues. Prof. Finley asked the hard questions and made me think twice about the role of science and how to make it relevant to our daily life. These helped me clarify my own ideas, and for that, I thank you!

There is more than one reason why I am thankful to have known Prof. Frances Lawrenz. For one, she has taught me a good deal about qualitative data analysis and all I needed to know about evaluation and measurement. Secondly, as a renowned expert of mixed methods, having her as part of my committee was precious. In her capacity as a member of my committee, she provided a valuable feedback that strengthened my work and made it more nuanced. I have enjoyed working with Frances this past couple of years on an evaluation project and thank her whole heartedly for all of her help and for pushing me to do my best, both in my dissertation work and the evaluation project.

I similarly owe profound debts to Professors Nathan Wood of North Dakota State University and Jamie L. Schneider of University of Wisconsin River Falls. Dr. Wood has been a colleague, member of my preliminary examination committee, and fellow chemistry educator. He has always been there for me, especially when I needed to brainstorm ideas for research and papers! This dissertation documents the fruition of a long-standing collaboration between Dr. Schneider, and the Chemistry Education Group spearheaded by Gill. Without Dr. Schneider's collaboration, much of this work would not have been possible. I am grateful to Dr. Schneider for the many insights she provided me as we worked on this project, and the effort and the time she has spent in developing with me the POGIL activities used in this study. We all owe you gratitude Dr. Schneider!

My sincere thanks also go to my fellow traveler and chemistry educator, James Nyachwaya (now Dr. Nyachwaya). James and I had many conversations about chemistry education and student representations of chemical reactions. The person who completes my inner circle of chemistry educators is Prof. Anne Kern of University of Idaho. Anne provided valuable insights that added weight to our work. I am grateful for her support and her continuous contribution to our little group. And to the newest member of the group, Anne Loyle-Langholz, for her help in data collection and analysis. Thanks Anne!

I have also benefited enormously from the institution I have been lucky enough to call home, the STEM Education Center at the University of Minnesota, and the colleagues and fellow students I am so fortunate to call friends. I am especially thankful for the friendship that Kristina Tank and Devarati Bhattacharya provided me. I have also enjoyed the friendship of Dr. Barbara Billington, Engin Karahan, Mary Hoelscher, David Groos, Dr. Rachel Haroldson, and countless other colleagues at the STEM Center. I am thankful to you all for your support and friendship. Similarly, I am grateful to the graduate school at the University of Minnesota and the Office of Diversity for the DOVE fellowship that funded my first year in the program. With the fellowship came a whole host of support mechanisms, so let me give a shout out to my fellow colleagues in the Community of Scholars Program (COSP).

At last but not least, let me acknowledge the support and the sacrifices my family endured during the course of my studies. I can honestly say, above all else, this work would not have been possible if they hadn't been there for me. Fosiya, your love and support sustained me through it all! I am wholeheartedly indebted to you and appreciate your encouragement, understanding, and patience with me. Thank you for putting up with my laptop and solitary confinement in the basement! Thank you for taking the kids to the park because I needed to finish up this piece of writing or that. And kids … you have sacrificed so much time I could have spent with you that I owe you a lifetime of gratitude. I am afraid I will need more of your sacrifice and understanding in the coming years. I appreciate it all and thank you from the bottom of my heart!

Dedication

This dissertation is dedicated to my family, immediate and distant, for the love and support they have provided me throughout my life. The proverbial African saying "it takes a village to raise a child" aptly applies ... *you have all made me who I am today and I dedicate this study to you all*.

To Fosiya, the love of my life, and my beautiful daughters (Samira and Ugbad) and boys (Anas, Salman, Ayyub, and Adnan) ... for your love, support, and understanding. You have sacrificed a lot for me.

To my mom, for her patience with me ... *Hooyo, nimaad dhashay kuma dhalin* (Somali)

To my old man, may he rest in peace!

And finally, to my siblings, for keeping my feet to the fire and encouraging me to take this journey that few dared to dream.

With love from dissertation land!

Abstract

Using the symbolic interactionist perspective that meaning is constituted as individuals interact with one another, this study examined how group thinking during cooperative inquiry-based activity on chemical bonding theories shaped and influenced college students' understanding of the properties of ionic compounds in solution. The analysis revealed the development of sociochemical norms and specific ways of reasoning about chemical ideas that led to shifts in student thinking and understanding of the nature of dissolved ionic solids. The analysis similarly revealed two kinds of teacher-initiated discourses, dialogical and monologic, that impacted student learning differently. I discuss the nature of this teacher-initiated discourse and number of moves, such as confirming, communicative, and re-orienting, that the course instructor made to communicate to students what counts as justifiable chemical reasoning and appropriate representations of chemical knowledge. I further describe the use of sociochemical dialogues as lens to study the ways in which chemistry instructors and students develop normative ways of reasoning and chemical justifications.

Because the activity was designed as an intervention to target student misconceptions about ionic bonding, I also examined the extent to which the activity elicited and corrected commonly found student chemical misconceptions. To do so, student-generated particulate drawings were coded qualitatively into one of four broad themes: i) use of molecular framework with discrete atoms, ii) use of ionic framework with discrete ionic species, iii) use of quasi-ionic framework with partial ionic-molecular thinking, or iv) use of an all-encompassing “other” category.

The findings suggested the intervention significantly improved students’ conceptual knowledge of ionic compounds in solution - there was statistically significant increase in the number of drawings using ionic and quasi-ionic frameworks in the pre-activity vs. post-activity (2.3% vs. 59.5%, $\chi^2(1) = 129.16$, $p < 0.001$) and significant reduction in the number of ionic compounds represented as molecular in the pre-activity vs. post-activity (71.2% vs. 24.1%, $\chi^2(1) = 72.24$, $p < 0.001$). I discuss these findings and their implications for research and teaching.

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List of Abbreviations

CL	Cooperative learning
POGIL	Process-oriented guided-inquiry learning
STEM	Science, technology, engineering, and mathematics

CHAPTER 1

Introduction and Rationale

"The balancing part was easy ... I had difficulty with how to draw the molecules, whether I should attach them all or separate them?"
Student response, pre-assessment test on ionic compound drawing task

"I am confident with balancing the equations. I really struggled with the idea of how the atoms, ions, and molecules would look during the reaction"
Student response, pre-assessment test on ionic compound drawing task

When researchers ask students of all ages to imagine seeing the atoms, ions, and molecules in chemical compounds and draw them, most students use a molecular framework to represent all chemical compounds, whether ionic, metallic, or molecular (Taber, 1998). Such responses reveal students' doubts about how to represent chemical reactions at the atomic/molecular level. Research in this area reveals two things: (1) Most students think of ionic compounds, such as sodium chloride (NaCl) salt, as molecular entities and (2) many students can mathematically balance chemical equations without understanding what the equations represent at the particulate level (Kern, Wood, Roehrig & Nyachwaya,, 2010).

Research in this area has mainly documented the range of misconceptions students hold about ionic compounds, with only a few studies exploring the "hows" and “whys” of conceptual development and growth (Taber, 2000). It is the latter, a move towards theoretically grounded studies that explore the hows and whys of conceptual development, that holds the promise to impact the teaching of chemistry and be most useful in terms of improving student learning (Taber, 2000). Thus, this work contributes to emerging studies in the field of chemistry education that blur the line between pure research and applied research. While it catalogs the diverse ways in which students represent ionic compounds at atomic/molecular levels, at the same time it explores the ways in which targeted instruction can improve students' conceptual knowledge growth. In this chapter, I provide a full description of the study’s rationale and research questions but first provide a brief overview of the dissertation’s organizational structure.

While I remain faithful to traditional dissertation format, chapter 1 providing and introduction and rationale, chapter 2 a literature review of relevant background material, chapter 3 my research methodologies, and the remaining chapters providing a discussion of main findings and implications, there are two ways in which I depart from this format. First, theoretical groundings and supporting literature for framing the study are described in this chapter. I believe coverage of this material early provides solid foundation for the rest of the study. Secondly, while the literature separately reviewed in chapter two frames the study as a whole, for instance by discussing pedagogies of engagement and the importance of discourse practices, nevertheless I use extant literature throughout the remaining chapters to frame analysis and discussion. Thus, the reader will come across discussion of available literature both in chapter two and in subsequent chapters. Grounding findings this way, rather than confining review of all literature to chapter two, provides as clearer application of relevant theories to problems under discussion and is more useful, I believe, in terms of understanding the findings.

1.1. Statement of the problem

During the last several decades a large body of research has described the particulate nature of matter (PNM) and its importance for understanding chemistry (e.g. Gabel, 1998; Krajcik, 1991; Harrison & Treagust, 2002). PNM refers to the atomic, molecular, and ionic interactions that lead to observable chemical phenomena (Gabel, 1999). Understanding PNM requires the ability to represent and translate chemical problems using three forms of representations—symbolic, macroscopic, and particulate (Johnstone, 1991) (see Figure 1.1).

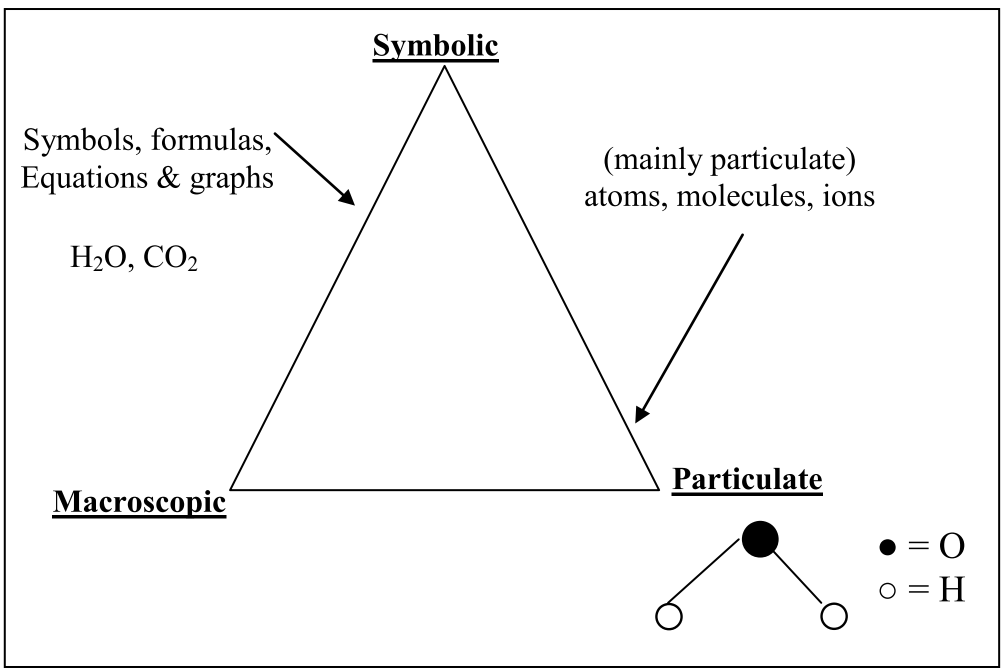


Figure 1.1. Johnstone's triangular model of chemistry representations

The symbolic level involves the use of chemical and mathematical notations and equations, whereas macroscopic representations describe observable and tangible properties of matter. At the particulate level, matter is represented in terms of its constituent particles, such as atoms, ions and molecules. Fluency in these representational forms and the ability to facilely shift between them is essential for understanding and learning chemistry (Krajcik, 1991; Russell, Kozma, Jones, Wykoff, Marx & Davis., 1997; Treagust, Chittleborough, & Mamiala, 2003). Unfortunately, chemistry students of all ages and educational levels lack this pre-requisite representational fluency, necessitating the need for instructional intervention.

A particular area in which students seem to have great difficulty is the ability to represent ionic compounds at the particulate level (Taber, 1998). When asked to represent ionic compounds at the particulate level, students appear to use molecular bonding framework (Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011; Taber, 1998). A word about chemical bonds may be necessary here. Chemical bonds are often classified in terms of how the electrons forming them behave: bonds resulting from electron sharing are defined as covalent bonds whereas those that form as a result of electrostatic interactions between ionic centers are defined as ionic bonds. Needless to say covalent bonds lead to the formation of molecular compounds (e.g. carbon dioxide, CO_2) and ionic bonds lead to the formation of ionic compounds (e.g. calcium chloride, $CaCl_2$).

The use of the molecular bonding framework, for instance using touching circles and lines to represent $CaCl_2$ (Cl—Ca—Cl), is contrary to the accepted scientific notion of crystal lattices for solid ionic compounds or, if in aqueous environment, particles with appropriate ionic charges separated in space and randomly distributed (Taber, 1998). One remedy for this may be to transform how chemistry is taught and make it relevant to students. Thus, investigating the impact different instructional approaches have on students' particulate representation of ionic compounds and understanding theories of chemical bonding is imperative for improving student learning of chemistry.

While Johnstone's three representational levels of macroscopic, symbolic, and particulate provide framework for the learning and the teaching of chemistry, studies have indicated that expert chemists can fluidly navigate between the three representational levels whereas novices have difficulty doing so (Hinton & Nakhleh, 1999; Nakhleh, 1992). I further describe Johnstone's model and its limitations in chapter two – for instance how the model does not take into consideration the role language and problem relevancy play in problem-solving and conceptual understanding. For now, however, I would like to emphasize that representational fluency in all levels can be developed and nurtured through instructional strategies that not only foster conceptual understanding of chemical ideas but also enhance student abilities to relate the particulate level to the symbolic realm. ***This study, therefore, sought to explore how group thinking during cooperative inquiry-based activities, namely Process-Oriented Guided-Inquiry Learning (POGIL), shapes and influences individual understandings of ionic compounds in solution and the effects of the intervention on students' representational fluency and conceptual growth.*** In particular, it explores the extent to which a POGIL intervention elicits and corrects alternate conceptions about ionic bonding that have been found to be commonplace among students (Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011; Taber, 1998).

1.2. Study purpose and research questions

The purpose of the study is to examine how cooperative inquiry-based activities, such as POGIL, impact students' representations of ionic compounds in solution and how group thinking during the POGIL activities shape individual understandings of ionic bonding. The guiding research questions are:

Research question 1: *How does group thinking during a cooperative inquiry-based activity on chemical bonding influence college students' conceptions of ionic compounds in solution***?**

Research question 2: *How do teachers' practical moves influence students' meaning making processes and sociochemical norms?*

Research question 3: *How do cooperative inquiry-based pedagogies, namely POGIL pedagogy, impact student understanding of the nature of ionic compounds in solution?*

The second research question, *how do teachers' practical moves influence students' meaning making processes and sociochemical norms*, was not planned ahead but became apparent as data collection and classroom observations ensued. As data analysis occurred, the course instructor's pedagogy, for instance scaffolding moves and direct dialogue with student groups, was revealed to impact the nature of classroom discourse. The teacher's practical moves, in this sense, became important part of the research agenda.

1.3. Instructional framework

The instructional strategy in the present study is Process-Oriented Guided-Inquiry Learning (POGIL), a pedagogical approach championed in chemistry departments in mid-1990s (Farrell, Moog, & Spencer, 1999; Spencer & Moog, 2008). While I describe the theoretical basis for using POGIL as a research instrument in the next section (section 1.3.2.), I will first briefly describe POGIL and what separates it from other pedagogical approaches.

1.3.1. Defining Process-Oriented Guided-Inquiry Learning (POGIL)

POGIL is an inquiry-based, constructivist pedagogy that seeks to simultaneously teach content and key process skills such as the ability to think analytically and work effectively as part of a collaborative team (Farrell, Moog, & Spencer, 1999; Spencer, 1999, 2006; Spencer & Moog, 2008). The key components of POGIL are the "active engagement of all students through group learning, guided inquiry materials based on the learning cycle paradigm, and a focus on process skill development (Moog, Creegan, Hanson, Spencer & Straumanis, 2006, p.42)." POGIL activities are done in groups of 3-4 students that self-organize within the large lecture hall or discussion classroom. Each group completes one guided inquiry worksheet and one group report form while the instructor moves around the classroom answering individual group questions as well as pausing discussions for whole class discussion and sharing of responses. The group report form assigns to each student a role such as manager, recorder, presenter, and reflector/skeptic (see appendix A for the group form used in this study). The group report form also asks students to record answers to key questions within the POGIL activity and to complete a short metacognitive reflection on group dynamics and/or group confidence in the POGIL activity material. Thus, POGIL forces students to verbalize their thinking about chemical ideas and elicits group construction or the social construction of concept understanding and knowledge growth.

1.3.2. Theoretical grounds for the instructional approach

The theoretical basis for using POGIL pedagogy is grounded in its constructivist, learning cycle paradigm approach. Constructivism, as discussed in chapter two, is theory of both knowing and learning, positing that knowledge is internally constructed and tested through interaction with the outside world (Ausbel, 1968). Since knowledge is internally constructed, it follows then that learning must occur via the construction of meaning in social contexts, within diverse cultures and languages. Consequently, the awareness of the 'social construction of knowledge' suggests a pedagogical emphasis on discussion, collaboration, negotiation, and shared meanings (Ernest, 1995).

As a pedagogy that emphasizes cooperative group learning, inquiry learning, and acquisition of process skills, POGIL can be used to probe the preconceived and alternate conceptions college students have about ionic bonding and the multiple ways they represent their understanding of ionic bonding. Furthermore, POGIL's emphasis on collaboration and group thinking can be viewed as a shared construction of conceived understanding. This shared construction provides opportunities for conceptual knowledge growth that may result overcoming deeply held misconceptions about ionic bonding. Moreover, consistent with the constructivist ideas that what a learner already knows influences the outcomes of learning (Ausubel, 1968), POGIL is based on the view that learning is the result of constructing meaning based on students' experiences and prior knowledge (Spencer, 1999). Thus, POGIL activities use the learning cycle paradigm, with exploration (E), invention (I), and application (A) phases characterizing all POGIL activities.

In the context of the present study, the exploration phase of POGIL allows investigating prior experiences with and knowledge of ionic bonding – which can be qualitatively cataloged and quantized. The invention phase, on the other hand, allows capturing the qualitatively different ways in which college students conceive understanding of ionic bonding. Finally, the application phase of POGIL activities can be used to investigate what pre-conceived ideas and alternate conceptions are resistant to change and which ones are amenable to targeted instructional intervention. Similarly, pre- and post-activity instruments permit ways of quantifying the conceptual knowledge change in which the participants underwent as a result of the POGIL instructions. Thus, POGIL is an appropriate venue for exploring the preconceived and alternate conceptions students have about ionic bonding and for investigating occurrences of conceptual knowledge change.

There are other theoretical considerations for using POGIL pedagogy. For instance, as described in chapter 2, one difficulty in understanding the particulate nature of chemical bonds is related to the multiple levels of representations used in chemistry instruction to describe and explain chemical bonding theories (Yarroch, 1985; Harrison & Treaguest 2002; Gabel, 1996; Johnstone, 1991). In chemistry, chemical bonds are often represented by using either chemical diagrams (a particulate representation), symbolic or chemical formulas, or through macroscopic descriptions (Johnstone, 1991). The reader will find further descriptions of these representational forms and their pedagogical use in chapter two.

Here, it is worth pointing out how the POGIL activities used in the present study force students to observe macroscopic demonstrations of what happens to ionic compounds when placed in water and subsequently how the activities guide students to show particulate level understanding of the observed macroscopic properties and describe the macroscopic and the particulate ideas through symbolic representation in the form of chemical equations (see description of POGIL activities in chapter 3 and the full activity in Appendix B). This is different from the traditional emphasis of symbolic and macroscopic descriptions in college courses and by design starts with macroscopic observations followed by opportunities to conceptualize the observed macroscopic properties. This deliberate design is informed by emergent research from the cognitive sciences and learning theories.

1.4. Chapter summary

This chapter provided the rationale, purpose, and the theoretical underpinnings of the present study. Much has been written about student misconceptions and alternate conception about ionic compounds and dissolving ionic salts in water (Butts & Smith, 1987; Coll & Taylor, 2001; Ebenezer & Erickson, 1996; Smith & Metz, 1996; Naah & Sanger, 2012). Similarly, we know that students have a difficult time in understanding what happens at the particulate level of matter but seamlessly can solve problems at the symbolic level – for instance, mathematically manipulate chemical equations (Nakhleh, 1992; Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011; Yarroch, 1985). This study similarly notes how students represent dissolving ionic compounds in solution but goes further than simply documenting what misconceptions are present in student's work. Rather, it uses cooperative inquiry-based activities to analyze how group thinking influences individual student learning and how to target chemical misconceptions with instruction. In the next chapter, a detailed overview of the relevant literature is provided leading to a detailed description of the research methodologies in chapter 3.

CHAPTER 2

Review of Relevant Literature

"Research into learners' ideas has been (at least in part) moving beyond the "stamp collecting" stage of simply observing and recording the enormous range of misconceptions out there, to [studies] which try to explore the "hows" and "whys" of conceptual development. In time this research may prove to be of great value to classroom teachers."

Keith Taber, BERA Annual Meeting, September 2000

"The primary barrier to understanding chemistry is not the existence of the three levels of representing matter. It is that chemistry instruction occurs predominantly on the most abstract level, the symbolic level."

Dorothy Gabel, *J Chem. Educ*., 76 (1999), p.548

This chapter provides an overview of relevant literature in three sections, each with multiple subcategories. The first section (section 2.1) reviews literature specific to the study of chemistry and documented student difficulties with respect to ionic compounds, including common chemical misconceptions. The works of Keith Taber (1998), Dorothy Gable (1998), Mary Nakhleh (1992, 1999), Harrison and Treagust (2002), and countless other researchers who cataloged student misconceptions and difficulties in learning chemistry is reviewed here. Section 2.2 reviews literature on pedagogies of engagement and their use in chemistry classrooms as well as other major theoretical frameworks guiding this research, including symbolic interactionism and sociochemical norms. The last section, section 2.3, revisits an issue I briefly touched upon in chapter one – the issue of representational fluency. This separation, I believe, makes for a better reading and handle of the study. Needless to say, as Keith Taber (2000) points out in the opening remarks of this chapter, there has been a paradigm shift from simply documenting the "*enormous range of"* chemical misconceptions out there to studies that try to change how students learn chemistry while evaluating the impact of various pedagogical approaches on chemistry learning. The literature review and how it is presented reflects this shift.

2.1. Review of students' understanding of ionic bonding

Much of the existing literature in chemistry education deals with alternate conceptions and misconceptions related to ionic compounds and thus this review will start with literature on chemical misconceptions, particularly misconceptions related to the nature of ionic compounds in solution. Other theoretical frameworks guiding the study follow in sections 2.2 and 2.3, including a discussion on symbolic interactionism and sociochemical norms.

2.1.1. Chemistry misconceptions/alternate conceptions – an overview

Over the years, chemical educators have explored student conceptions of chemical ideas that significantly differ from scientifically accepted chemical explanations and the barriers such concepts create for further learning progressions in chemistry. The terms misconceptions, alternative/alternate misconceptions, conceptual frameworks, and preconceptions have all been used to describe these *differing conceptions* (Driver &

Easley, 1978; Driver & Erickson, 1983; Garnett and Treagust, 1990; Gilbert & Watts, 1983; Gilbert & Swift, 1985; Horton, 2007; Nakhleh, 1992; Osborne and Freyberg, 1985; Solomon, 1993; Taber, 1994, 1998, 2011). Other labels have also been used to describe these differing science concepts, especially among young children and learners, including *naive beliefs* (Caramazza, McCloskey, & Green, 1981), *naive theories* (Resnik, 1983), *naive conceptions* (Champagne, Gunstone, & Klopfer, 1983), *scientific intuitions* (Sutton, 1980), *children's science* (Gilbert, Osborne, & Fensham, 1982; Osborne, Bell, & Gilbert, 1983), *common sense understanding* (Hills, 1983), *common sense concepts* (Halloun & Hestenes, 1985), *intuitive conceptions* (Lee & Law, 2001), *intuitive science* (Preece, 1984), *common alternative science conceptions* (Gonzalez, 1997), *prescientific conceptions* (Good, 1991), and *alternate perceptions* (Carter & Brickhouse, 1989). The use of these various terms, states Ozmen (2004), "reflect the complex nature and multiple causes of children's erroneous conceptions as viewed by science educators" (p2).

Within the chemistry education community, the terms alternate conceptions and misconceptions are used synonymously (Bodner, 1991; Horton, 2007; Nakhleh, 1992; Taber, 2011) although their use at times has been problematized. Taber (2011), for instance, argues *misconceptions* suggest misunderstanding of canonical knowledge whereas *alternative conception* would include spontaneously developed understanding such as "intuitive notions acquired from direct experience of the world" (p.5). Horton (2007) similarly states misconceptions "seems excessively judgmental in view of the tentative nature of science and the fact that many of these conceptions have been useful to the students in the past."(p.1). The term *preconception is* similarly problematic in that it does not take into account the role classroom instructions play in forming these differing student conceptions.

In the current work, I use the terms *alternate conceptions* and *misconceptions* interchangeably to refer to any concepts that differ from the chemically accepted understanding of the term. This is consistent with the practice within the chemistry education community where, as mentioned above, these two terms are used interchangeably despite the assumptions inherent in their use.

2.1.2. Misconceptions across the chemistry curriculum

Chemical misconceptions have been observed in all areas of chemistry, including *chemical bonding* (Birk & Kurtz, 1999; Boo, 1998; Coll & Taylor, 2001, 2002; Coll &Treagust, 2001, 2002, 2003; Harrison & Treagust, 2002; Niaz, 2001; Nicoll, 2001; Peterson Treagust, & Garnett, 1986, 1989; Robinson, 1998; Taber, 1994; Tan and Treagust, 1999), *chemical reactions* (Andersson, 1990; Ayas & Demirbas, 2002; Ben-Zvi, Eylon, & Silberstein, 1987; Boo & Watson, 2001; Hesse & Anderson, 1992; Kern, Woods, Roehrig, & Nyachwaya, 2010; Nyachwaya, Mohamed, Roehrig, Wood, Kern, Schneider, 2011), *atoms, elements, molecules, compounds, and mixtures* (Ben-Zvi, Eylon, & Silberstein, 1986; Griffiths & Preston, 1992; Harrison & Treagust, 2000; Nakhleh & Samarapungavan, 1999; Sanger, 2000; Skamp, 1999; Stains & Talanquer, 2000), *acids and bases* (Bradley & Mosimege, 1998; Hand and Treagust, 1991; Nakhleh and Krajcik, 1994; Sisovic and Bojovic, 2000), and *solubility and solutions* (Ebenezer and Erickson, 1996; Ebenezer and Fraser, 2001; Smith and Metz, 1996).

Nakhleh (1992) provides a comprehensive review of several alternate conceptions students hold, including misconceptions of matter as a continuous medium as well as misconceptions related to the nature of atoms and molecules, molecules and intermolecular forces, phase changes, gases, chemical equilibrium, and chemical equations, and chemical reactions. Ozmen (2004) similarly provides a comprehensive review of literature describing misconceptions specifically related to chemical bonds. Other comprehensive reviews exist for other specific topic areas – for instance, acid and bases (Demircioglu, Ayas, & Demircioglu, 2005).

The chemical misconceptions reported in the literature tend to be persistent, stable, and common among students of all ages and school levels. For instance, Bodner (1991) reported that fully 30% of beginning chemistry graduate students failed to identify the bubbles in water that had been boiling for over an hour as water vapors; 20% thought the bubbles contained air and/or oxygen. None of the students were able to correctly describe the reaction of sodium metal with chlorine gas to form $Na^{+}Cl^{-}$. Similarly, Birk and Kurtz (1999) studied the effects of experience on the retention and elimination of misconceptions about molecular structure and bonding. Their subjects varied from high school students to college faculty. The authors reported most misconceptions persisted into graduate school and beyond. Lewis, Eileen, Linn, and Marcy (1994) also studied chemical misconceptions over a large range of chemical experience – from middle school students to college faculty holding advanced degrees in various sciences. All participants held similar misconceptions about the natural world regardless of their age or level of expertise except among those with PhDs.

The question of how chemical misconceptions arise has also been the subject of extensive research. Nakhleh (1992) uses a cognitive learning model in which learners are assumed to construct their own meaning of chemical concepts based on life experiences and previous knowledge to account for how chemical misconceptions arise. According to Nakhleh (1992), people use cognitive structures – a coherent understanding of world events and phenomena – to link and integrate similar concepts, for instance by forming integrated cognitive structures of chemical knowledge. Since students build their own concepts, it follows that sometimes their chemical constructs – say the nature of chemical bonding, for instance – will differ from the more scientifically accepted understandings of those same concepts. Nakhleh (1992) suggests it is when newly presented concepts or information cannot be appropriately integrated into existing cognitive structures or properly aligned with the pre-existing cognitive structures that weak understanding or misunderstandings of concepts occurs.

Horton (2007) similarly argues preconceptions form the mental framework, the scaffolding, on which students build all subsequent knowledge. Similar to Nakhleh (1992), Horton states new information must be rearranged to fit within the existing scaffolds. He writes:

> *"Given that these conceptions exist as actual physical pathways laid down in the brain and given that the cognitive architecture of the brain, once laid down, cannot be expunged but only overlaid with new paths, it is not surprising that it should be very difficult for students to move beyond them to the scientifically accepted concepts … [but] instead graft new knowledge onto a conceptually faulty base" (Horton, 2007, p.6).*

Hunt and Minstrell (1997), on the other hand, suggest children's misconceptions are the result of their prior concepts before teaching not being taken into consideration and therefore creating a communication gap between teachers and learners that inhibits proper student understanding of new concepts.

The foregoing studies describe the regularity of chemical misconceptions among students of all ages, school levels and in different areas of chemistry. They also speculated the plausible causes of these misconceptions. One active area of research, and of particular interest to this work, is students' conceptions of ionic compounds. The following paragraphs synthesize findings from several reports that describe students' conceptions of ionic compounds, including when such compounds are placed in water.

2.1.3. Student's understanding of the nature of ionic compounds

Taber (1998a) studied student conceptions of ionic bonds and found most students perceived bonding in materials like calcium chloride ($CaCl_2$) as molecular entities in which an otherwise discrete ionic pairs in such materials were shown as though they were covalently attached to each other. This observation led the author to identify a set of eight alternative conceptions about chemical bonding and the behavior of electrons in chemical reactions that many students hold. For instance, three misconceptions about ionic bonds were common among all the students the author studied (Taber, 1994, 1998):

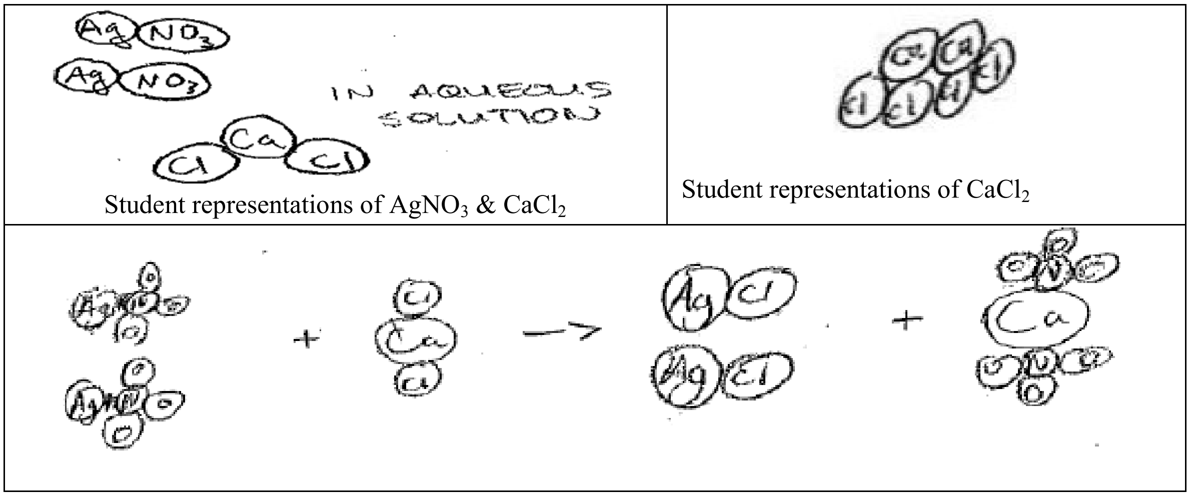
Misconception 1: charges limit the number of ionic bonds that can form

Misconception 2: ionic bonds exist only when there is an electron transfer between atoms to form ions

<u>Misconception 3</u>: *ionic lattices are comprised of ions that are ionically bonded to some counter-ions, and attracted to others by 'just forces' [not proper bonds]*

To Taber, these misconceptions suggested students were focusing entirely on electron transfer events to describe the nature of ionic bonding – an ionic compound forms when there is a transfer of electron from an atom losing an electron to an atom gaining an electron – as supposed to the idea that ionic bonds result from electrostatic attractions between ionic centers (Taber, 1994, 1998a). This is important because the misconception that *ionic bonds exist only as a result of electron transfer between atoms* becomes barrier to understanding the nature of ionic lattice or the fact that electrostatic interactions are not limited to ionic pairs but the availability of ionic centers in a given chemical environment (i.e., the chloride ion in NaCl is technically bonded to six different sodium ions in the NaCl lattice, not a single sodium ion).

Nyachwaya, Mohamed, Roehrig, Wood, Kern, and Schneider (2011) asked freshmen college students to imagine seeing the atoms, molecules and ions in the reaction of silver nitrate ($AgNO_3$) with calcium chloride ($CaCl_2$) and to draw particulate diagrams showing what they might see. Figure 2.1 shows sample student-generated drawings to represent this reaction. 73% of the student drawings in this study did not distinguish between covalent and ionic bonding, with ionic materials such as $CaCl_2$ and $AgNO_3$ shown as though they were covalently attached to each other. Note how, in the drawings in Figure 2.1, the $CaCl_2$ is shown in a bent molecular shape as if there are the same electron repulsion phenomena one will find in water molecules.



Student representations of $AgNO_3$ & $CaCl_2$

Student representations of $CaCl_2$

Figure 2.1. Student-generated drawings of of $AgNO_3$ and $CaCl_2$ from Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider (2011)

The findings in the Nyachwaya et al (2011) study are consistent with the alternative molecular framework proposed by Taber (1998) in which students perceive bonding in ionic compounds as molecular entities with otherwise discrete ionic pairs shown as covalently attached to each other. They are also consistent with findings from the study by Peterson, Treagust, and Garnett (1989). Peterson et al reported high school students thought ionic charges determine the polarity of bonds as supposed to electronegativity and used covalent bonding concepts to describe ionic lattices. Butts and Smith (1987) studied high school student's understanding of the structure and properties of molecular and ionic compounds and found some students thought the sodium and chlorine ions in NaCl were held together by a covalent bond. Coll and Taylor (2001) similarly found students in their study perceived continuous ionic lattices as molecular in nature, in addition to confusion over ionic sizes.

The emerging picture from the foregoing studies depicts chemistry students of all ages and educational levels having difficulty conceptualizing the nature of ionic bonds and using alternative frameworks to describe the bonding within ionic compounds. The list of misconceptions identified in these studies impedes further conceptualization of the properties of ionic compounds. For instance, it is likely that students who hold these misconceptions will have difficulty understanding how ionic compounds behave in aqueous solutions (if a student believes ionic compounds are held together by covalent bonds, it is unlikely the student will show dissolution of ionic solids into discrete ions randomly separated in space when in aqueous environment). The following paragraphs review literature that specifically examines students' conceptions of ionic compounds in solution.

2.1.4. Student's conceptions of ionic compounds in solution

Several authors have studied students' conceptions of ionic compounds in water and revealed major misconceptions students hold about the dissolution of ionic solids in water, including the notion that *dissolved ionic compounds react with water to form an acid and a metal* oxide (Naah & Sanger, 2012, 2012; Tien, Tiechert, & Rickey, 2007), *ionic solids dissolve as neutral atoms or molecules* (Ebenezer, 2001; Ebenezer & Erickson, 1996; Naah & Sanger, 2012; Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011; Smith & Metz, 1996; Tien, Tiechert, & Rickey, 2007), *ions in dissolving salt compounds form ion-dipole intermolecular forces with water* (Tien, Tiechert & Rickey, 2007; Smith & Nakhleh, 2011), *ions in dissolving salts form intermolecular forces between "the salt molecules"* (Smith and Nakhleh, 2011), *polyatomic ions dissociate as discrete ions* (Naah & Sanger, 2012; Nyachwaya, Mohamed, Roehrig, Wood, Kern, & Schneider, 2011; Smith & Metz, 1996; Tien, Tiechert, & Rickey, 2007), and *confusion of oxidation states, subscripts, and coefficients in chemical equations* (Naah & Sanger, 2011; Nyachwaya, Mohamed, Roehrig, Wood, Kern, & Schneider, 2011; Tien, Tiechert, & Rickey, 2007). The following will highlight some of the findings from these studies.

2.1.4.1. Students' particulate drawings of dissolved ionic solids

Several of the studies mentioned above evaluated students' understanding of solution chemistry through particulate representations (Smith and Metz, 1996). Figure 2.2, for instance, shows the item Smith and Metz (1996) used to elicit their subjects' understanding of solution chemistry. In the item shown, participants were asked to draw particulate-level diagrams that shows what happens when nickel (II) chloride reacts with sodium hydroxide (NaOH) to form nickel (II) hydroxide ($Ni(OH)_2$) and sodium chloride (NaCl). Only 7% of undergraduate chemistry students drew appropriate particulate representations of the reactants and products in the reaction mixture. Tien, Tiechert, and Rickey (2007) similarly asked students, through a unique laboratory module called MORE (Model-Observe-Reflect-Explain), to generate initial models that represent what they think NaCl looks like at particulate level. The students subsequently investigated the nature of NaCl dissolution in the laboratory setting. In their initial particulate drawings, before exposure to the MORE modules, only 35% of the students had a correct molecular model of aqueous NaCl while 32% did so for sugar dissolved in water. These studies were consistent with respect to the difficulty students had representing ionic solids at the particulate level.

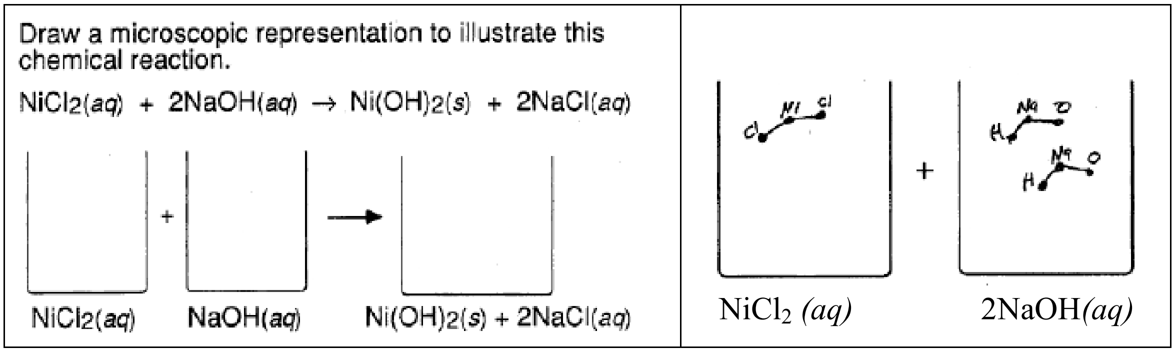


Figure 2.2. Prompt question used to elicit students' particulate conceptions of the reaction between nickel (II) chloride and sodium hydroxide (left panel) and sample student response (right panel) (From Smith and Metz, 1996, *J. Chem. Educ.*, 73 (3), 233–235).

2.1.4.2. Students' symbolic representations of dissolved ionic solids

Several studies specifically looked at how students represented dissolved ionic solids at the symbolic level. Students often selected symbolic equations showing ionic salts reacting with water via double displacement mechanism (Naah & Sanger, 2012) or dissociating as neutral atoms or molecules (Kelly & Jones, 2007; Naah & Sanger, 2012; Smith & Metz, 1996). Students also generally confused proper use of subscripts and coefficients and thought polyatomic ion dissociate into smaller components when dissolved in water (Naah & Sanger, 2012; Nyachwaya, Mohamed, Roehrig, Wood, Kern and Schneider, 2011). These finding suggest students can mathematically manipulate chemical equations but do not necessarily understand what the equations represent (Nakhleh, 1992; Nyachwaya, Mohamed, Roehrig, Wood, Kern and Schneider, 2011; Yarroch, 1985).

2.1.4.3. Interventional studies targeting student misconceptions

Several of the studies reviewed above included instructional interventions intended to alleviate students' misconceptions about the dissolution process including the use of hypermedia, computer animations, multi-media based instructions, and various active learning strategies, including hands-on laboratory activities (Bruck, Bruck & Phelps , 2010; Ebenezer, 2001; Kelly & Jones, 2007, 2008; Naah & Sanger, 2013: Tien, Tiechert & Rickey, 2007). In general, these studies showed improved student understanding of the nature of dissolving ionic solids after the interventions although certain misconceptions remained unchanged (Kelly & Jones, 2008; Tien, Tiechert, and Rickey, 2007).

Findings from these studies suggest appropriate teaching strategies can promote students' deep-level understanding of the dissolution process. However, beyond the use of computers and laboratory settings, what is needed is a paradigm shift in the way chemistry instructions is done, as Dorothy Gabel (1999) so aptly stated in the opening remarks of this chapter – "*The primary barrier to understanding chemistry is not the existence of the three levels of representing matter. It is that chemistry instruction occurs predominantly on the most abstract level, the symbolic level*" (Gabel, 1999). The next section (Section 2.2), therefore, reviews literature related to pedagogies of engagement in the chemistry classrooms.

2.2. Pedagogical approaches to learning

For more than two decades there has been a gradual shift towards cooperative and inquiry-based pedagogies in college chemistry teaching (Coppola, 1996; Eikls, Markic, Baumer, & Schanze, 2009; Cooper, 1994; Spencer, 1999, 2006). The success of these newer pedagogies in the teaching of chemistry in part stems from their ability to foster student discussion and create collaborative learning dynamics in a social context wherein problem-solving and conceptual understanding is stressed (Basili & Sanford 1991; Johnson, Johnson & Smith, 1991). Moreover, statistical analyses of measures of student achievement and learning gains have shown cooperative and inquiry-based pedagogies having positive impact on student learning in chemistry (Bowen, 2000; Lewis & Lewis, 2005; Paulson, 1999). Consequently, cooperative learning and inquiry approaches have been widely embraced by the chemical education community. The following paragraphs review these pedagogies and their role in chemistry teaching and learning.

2.2.1. Cooperative inquiry-based pedagogies

Cooperative learning is not a new phenomenon but one with a long tradition and history. Its definition has evolved over the years to represent different forms of classroom cooperation. Johnson, Johnson, and Holubec (2008) define it as "the instructional use of small groups so that students work together to maximize their own and each other's learning" (p.5). This, then, contrasts it with traditional learning methods in which competitive or individualistic learning modes dominate (Johnson, Johnson & Smith, 1991). Under competitive learning environment, the assumption is students work against each other to achieve academic goal that only one or few students can attain (to achieve success, others must fail). In individualistic learning, accomplishing learning goals is an individualistic endeavor unrelated to other students' achievement (students work by themselves to achieve academic success). Cooperative learning, on the other hand, suggests students work together to reach common goal and succeed as a group.

Johnson, Johnson, and Smith (1991) point to five key elements that make up all effective cooperative learning activities. These elements, with brief descriptions, are:

1. **Positive social interdependence**: members rely on each other to complete given task and maximize group productivity. The cliché *sink or swim together* aptly describes this phenomenon.
2. **Individual accountability:** individual students master the material and share their knowledge with group members. To hold individuals accountable for learning the material, each member is asked to demonstrate his or her learning with individual assessment, the results of which are given to the group and the individual.
3. **Face-to-face interaction**: team members promote each other's learning by helping, sharing, and encouraging efforts to produce results. To achieve this, team interactions must be based on eye-to-eye contact that permits group discussion and direct teaching.
4. **Interpersonal and small group skills**: students are given opportunities to develop needed social skills, such as effective communication skills, conflict resolution, trust-building, and decision making. These skills are emphasized intentionally and their importance as performance skills reiterated continuously.
5. **Group processing**: teams are given both space and time to discuss how well they are achieving their goals and maintain effective working relationships.

Johnson, Johnson and Smith (1991) suggest cooperative learning methods create an active learning environment where students are engaged in the learning process and become active agents of their own learning. Studies evaluating the effectiveness of cooperative learning appear to corroborate that assertion. For instance, a meta-analysis of cooperative learning groups showed it promoted student learning including academic achievement, science attitudes and persistence (Springer, Stanne & Donovan, 1997). In an earlier study, Humphrey, Johnson and Johnson (1982) contrasted the effectiveness of cooperative learning with competitive and individualistic learning and reported cooperative learning resulted better student learning outcomes. Thurston, Topping, Tolmie, Christie, Karagiannidou and Murray (2010) similarly examined cooperative learning in science by following sample of students transitioning from primary to high school in England and found content learned in the original study persisted overtime.

In chemistry, POGIL materials, such as the ones used in this study, attempt to incorporate the elements of cooperative learning into classroom activities, with specific attention paid to the elements of *positive interdependence, interpersonal and social skills, and group processing.* For instance, POGIL groups turn in one consensus-checked final group report at the end of each class session (see appendix A for sample report). The intent of such group report is to purposefully create positive interdependence within the student groups. Aside from the POGIL project, there exists a large literature in the chemistry education field reporting implementation of cooperative learning strategies in chemistry classrooms. The following section briefly discusses this literature.

2.2.1.1. Transforming chemistry teaching

The shift in chemistry towards cooperative learning has been mainly driven by dissatisfaction with traditional teaching methods (Cooper, 1995; Coppola, 1996; Coppola & Lawton, 1995; Fleming, 1995; Spencer, 1999, 2006; Towns, 1998) that led to numerous studies reporting the implementation of cooperative learning in chemistry classrooms at the college level. Several of these studies reported significant and positive effects of cooperative learning on chemistry achievement (Bowen, 2000; Sandi-Urena, Cooper, Gatlin & Bhattacharyya, 2011; Towns, Kreke, and Fields, 2000). For instance, Bowen (2000) conducted a meta-analysis involving a total of 475 high school students and almost 1,100 college students taught by using various forms of cooperative learning. The author reported that, on average, using aspects of cooperative learning enhanced chemistry achievement for both high school and college students (mean effect size of 0.37 with a standard deviation of 0.39). An earlier study by Springer, Stanne and Donovan (1997) similarly showed cooperative learning had significant impact on achievement-related outcomes for college students in Science, Mathematics, Engineering and Technology (SMET) courses.

Several explanations have been put forth as to why cooperative learning methods positively impact student learning. Noel (1990) argues cooperative learning maximizes student engagement in the learning process while Worrell (1992) suggests active learning strategies, including cooperative learning, create excitement in the chemistry classroom. Coppola (1996) provides a succinct review that suggests group-based work in collaborative and cooperative learning groups promote more active engagement by students in their own learning, emphasize the role of teachers and students as learners who benefit from teaching one another and create opportunities to develop important higher order interpersonal and group skills that can "promote the development of self-learning skills so that students can deal with new information rather than only relying on authorities to 'cover' content" (Coppola, 1996, p. 1432). Others suggest cooperative learning creates learning environments "rich in opportunities for metacognitive practice"

(Sandi-Urena, Cooper, Gatlin & Bhattacharyya, 2011, p. 441). In a more recent paper, Karacop and Doymus (2013) investigated the effects of jigsaw cooperative learning and computer animations techniques on academic achievement of students in first year general college chemistry. The authors found that the teaching of chemical bonding via the animation and jigsaw techniques was more effective than traditional teaching methods in increasing students' academic achievement.

In summary, the studies on cooperative learning in chemistry are generally in agreement that cooperative learning strategies enhance student understanding of chemical concepts, promote positive attitudes towards the learning processes, and result in persistent gain of academic achievement outcomes (Bowen, 2000; Sandi-Urena, Cooper, Gatlin and Bhattacharyya, 2011; Springer, Stanne and Donovan, 1997). Such findings have implication for curricular design efforts and future research designs. With respect to the present study, the opportunities for social interactions provided by the cooperative activities in POGIL allowed me to examine how group thinking influenced individual learning. The next section provides the theoretical grounds for using social interactions as a mechanism to investigate how group thinking influenced individual learning.

2.3. Symbolic interactionism as theoretical framework

The main theoretical framework described in chapter one was the constructivist and social constructivism theories of Piaget (1968) and Vygostk (1978) as theoretical basis for the POGIL activities in this study. In this section, I discuss other theoretical frameworks that inform the study, namely symbolic interactionism and representational fluency. Under the symbolic interactionism heading, I describe sociomathematical and sociochemical norms – disciplinary social constructs that describe how classroom dynamics impact student development of chemical and mathematical beliefs and values. The analysis of the data shown in chapter four is mainly driven by the symbolic interactionist perspective used to analyze student discourses captured during audio-recorded group dialogues.

2.3.1. Symbolic Interactionism

One of the guiding theoretical frameworks in this research is the interpretive symbolic interactionist perspective advanced by Herbert Blumer (1969) and others. In this framework, individuals are thought to constitute collective understanding of ideas through interaction with one another and by sharing perspectives or developing common definitions - meaning making, in this case, is subject to group negotiation and thus the emphasis on social interactions and social contexts (Bogden & Biklen, 2003). There are two reasons why I find the symbolic interactionist perspective useful for this study. First, this research is conducted in a cooperative inquiry-oriented setting in which face-to-face interactions and positive interdependence are essential features of the classroom micro-culture (Johnson, Johnson & Smith, 1991; Moog, 2008). Symbolic interactionism allows one to examine "how individuals are able to take one another's perspective and learn meanings and symbols in concrete instances of setting" (Jacob, 1987, p.29) such as the one described in this study.

Second, the constructivist theories of Piaget and the belief that learning is the most powerful when students construct their own knowledge, pose questions and find answers collectively (Ausbel, 1968; Piaget, 1973; Vygotsky, 1978) form the basis of the classroom activity used in this study. The construction of knowledge in this instance, however, is occurring in a social context where students are co-constructing and negotiating chemical meaning-making processes as a group. This aligns with the principles of symbolic interactionism and the idea that individuals constitute meaning through interaction with each other.

Yackel and Cobb (1996) and Becker, Rasmussen, Sweeney, Wawro, Towns and Cole (2012) particularly emphasize how neither the individual nor the social is taken as primary in the symbolic interactionist perspective; rather, individual students develop personal understandings through classroom discourse and interactions. This bodes well for the aims of this study – to understand the relationship between theoretically-based instructional activities (i.e., cooperative learning) and the teaching and learning of chemistry in a classroom setting with its own unique social norms and customs (a "pogil-ized" classroom, if you may). These specific social norms and customs are described below.

2.3.2. Sociochemical/sociomathematical norms – disciplinary social norms defined

Becker, Rasmussen, Sweeney, Wawro, Towns and Cole (2012) recently coined the term *sociochemical norms* to describe the disciplinary criteria that regulate classroom discourse and normative aspects in the study of chemistry. These authors extended the social construct of *sociomathematical norms* to the field of chemistry, a notion advanced by Yackel and Cobb (1996) as a way to interpret how mathematics classroom dynamics impact student development of mathematical beliefs and values. A brief discussion of sociomathematical norms is warranted before I describe sociochemical norms.

2.3.2.1. Sociomathematical norms

Yackel and Cobb (1996) advanced the notion of sociomathematical norms as a social construct that describes normative aspects of mathematics discussions specific to students' mathematical ability. This is in contrast to the general classroom social norms and customs such as the ability to explain a problem or ways of thinking about the problem that one would expect to observe. For instance, in general classroom discourse, it is expected participants will argue and explain their thinking to each other, listen to and make sense of other's reasoning and arguments, and voice their agreement or disagreements with others (Becker, Rasmussen, Sweeney, Wawro, Towns & Cole, 2012). Such behaviors and ways of acting are expected to become the norm in inquiry-oriented settings where discourse practices occur frequently within groups or at the whole-class level. These normative ways of acting, however, are discipline-independent –discussions could be about mathematics or physics or chemistry problem and certain ways of acting would become normative irrespective of the subject (Becker, Rasmussen, Sweeney, Wawro, Towns an Cole, 2012; Yackel & Cobb, 1996; Yackel, Cobb & Wood, 1999).

Sociomathematical norms, in contrast to the description of social norms above, are disciplinary criterion for *what counts* as an acceptable mathematical explanation and/or justification. Its relative normalcy becomes apparent only in the context of mathematics. For example, Yackel and Cobb (1996) observed a second-grade classroom where the children's task was to mentally add 16 + 14 + 8 without access to paper and pencil. Multiple students in the study provided different mathematical justifications of how they solved the problem. One student stated they added the two one's out of 16 and 14 to get

20, added the 6 and the 4 to get 10, then added the 10 and 20 to get 30, and finally added the 30 and 8 to get 38. Following the student's response, the teacher asked if anyone else "added a little *differently*?" (Yackel & Cobb, 1996, p.463). Here, the teacher was eliciting for other responses that might *count as mathematically acceptable and justifiable*, other ways of mathematically adding 16 + 14 + 8, not different ways of explaining the student's response.

Yackel and Cobb (1996) interpreted the foregoing exchange to suggest the teacher and the students were in the process of constituting mathematical meaning and providing mathematical justifications to support their summation of 16 and 14. The teacher in the above exchange in the Yackel–Cobb study routinely asked the students if anyone added a *little differently* and questioned contributions they did not consider to be mathematically different. Here, "different" meant what counts as different mathematically, not in the general sense of reconstituting something new, something different. Yackel and Cobb (1996) argue that the particular thinking involved here and the mathematical justifications that became normative within the classroom were intrinsic aspects of the classroom's mathematical microculture (Yackel & Cobb, 1996). For instance, in the above exchange, the children "learned that the teacher legitimized solutions that consisted of partitioning the summands and recombining the results in various ways but offered sanctions against those that were restatements of the previously-given solutions" (Yackel & Cobb, 1996, p. 4168). Thus ideas were taken-as-shared and become normative within the class.

2.3.2.2. Sociochemical norms

Cole, Becker, Towns, Sweeney, Wawro and Rasmussen (2011) recently studied classroom discourse in an undergraduate physical chemistry course with the aim of examining the collective development of ideas taken-as-shared and how communities of learners establish such ideas through discourse and inquiry. The authors use the term "classroom chemistry practice" to refer to the normative ways of reasoning that develop as students work together to solve problems, explain their thinking, and entertain opposing points of view. They used Toulman's argumentation model to determine specific ways of reasoning that became part of normative chemistry classroom practices. For instance, particulate-level descriptions of solids, liquids, and gases became "central to the collective reasoning about thermodynamic concepts and processes" (Cole, Becker, Towns, Sweeney, Wawro and Rasmussen, 2011, p14). This particulate-level reasoning is discipline-specific justification of what counts as chemically justifiable and acceptable and hence a sociochemical norm as supposed to general classroom social norm.

In extending the social construct of sociomathematical norm to the field of chemistry, Becker, Rasmussen, Sweeney, Wawro, Towns and Cole (2012) argued that sociochemical norms describe the disciplinary criteria that regulate classroom discourse and normative aspects in the study of chemistry. The students' particulate-level reasoning about thermodynamic concepts and processes and the phases of matter in the study above by Cole and colleagues (2012) suggests these practices became normative aspects of the chemistry classroom as they would have not, say, in a mathematics classroom.

In this work, I align with Becker and colleagues (2012) in that I believe there are normative aspects of chemistry discussions specific to the field of chemistry and describe, in chapter four, the processes by which sociochemical norms related to the nature of chemical compounds in solution are established. These sociochemical norms can influence personal understandings and students' conceptions of ionic compounds in solution, particularly in cooperative inquiry-oriented settings where both instructor and students are involved in constituting what counts as an acceptable chemical explanation, reasoning, and justification.

It is also important to consider that sociochemical norms in inquiry-oriented settings allow students to develop intellectual autonomy as they learn to explain and justify their thinking to others, and in the process develop personal understanding of chemical ideas. Intellectual autonomy refers to an individual's participation in classroom interactions (Yackel & Cobb, 1996). Because intellectual autonomy can be fostered, it is reasonable to assume it is developed as chemistry instructors and students constitute sociochemical norms for the chemistry classroom.

Understanding sociochemical norms has implications for classroom pedagogy and curricular efforts. One could imagine, for instance, that different curricular activities result different discourse practices and classroom microcultures. For this reason, the POGIL activities used in this study were intentionally designed to include multiple representational forms. In the next section, I revisit the issue of representational fluency that was briefly described in chapter one.

2.4. Representational fluency revisited

In chapter one, I described how during the last several decades a large body of research described the particulate nature of matter (PNM) and its importance for understanding chemistry (Gabel, 1998; Krajcik, 1991; Harrison & Treagust, 2002). PNM, you may recall, refers to the atomic, molecular, and ionic interactions that lead to observable chemical phenomena (Gabel, 1999). The idea that understanding PNM requires the ability to represent and translate chemical problems using three forms of representations—symbolic, macroscopic, and particulate (Gabel, 1999; Johnstone, 1991; Harrison & Treagust, 2002)— has become paradigmatic in chemistry education. As a paradigmatic shift in the field, it influences curriculum reform efforts, classroom practices and research agendas (Talanquer, 2011).

In this and other works (Bruck, Bruck, Phelps, 2010; Naah & Sanger, 2012, 2013; Nyachwaya, Mohamed, Reohrig, Wood, Kern & Schneider, 2011; Smith and Metz, 1996; Smith and Nakhleh, 2011; Tien, Triechert & Rickey, 2007) the idea that chemical knowledge can be represented at the three above representational levels, referred to heretofore as the Johnstone Model, is central to the research agenda in these studies. For instance, Naah and Sanger (2013) compared how static and dynamic representations influenced students' particulate and symbolic level conceptions of dissolving ionic compounds. Similarly, Smith and Metz (1996) elicited students' alternative conceptions about dissolving ionic solids by asking students to generate particulate-level description of a chemical reaction. Davidowitz, Chittleborough and Murray (2010) advanced the notion of using student-generated particulate diagrams as a useful tool for teaching and learning chemical equations and stoichiometry. Kern, Roehrig, Wood and Nyachwaya (2010) examined how high school chemistry students represented the combustion of methane gas at the particulate level. In subsequent work, Nyachwaya, Mohamed, Reohrig, Wood, Kern & Schneider (2011) examined how college students represent chemical equations across reaction types. The Johnstone Model was a central feature in all of these studies.

Talanquer (2011) recently problematized the underlying assumptions of the Johnstone Model, for instance, by pointing out the various ways the three levels of the model have been described: levels of thought (Johnstone, 1991), modes (Johnstone, 1993), levels of description (Gabel, Samuel & Hunn, 1987), levels of teaching (Gabel, 1993), and levels of representations (Gabel, 1999: Gilbert & Treagust, 2009). Arguing that "levels of representations" has become the dominant view of the Johnstone Model in recent years, Talanquer (2011) asks "in which way can the *macro* level, of things that are visible and tangible, be called a "representation"? Or, why should we single out the *representational* level as one of the major components of the triplet if the other two major elements are also "levels of representation"?"(p181). It appears Talanquer equates the representational level on what happens at the symbolic level, not the particulate or the macroscopic levels. Nevertheless, problematizing the underlying assumptions of the Johnstone Model can lead to only clearer understanding.

Of particular interest to my work is Talanquer's (2011) argument for rethinking the symbolic level of the Johnstone Model. The symbolic level, as you may recall, refers to the chemical and mathematical notations and equations used to represent chemical concepts and ideas. Talanquer points out how some authors prefer “to separate the *symbolic system*, in which substances and processes are symbolized using chemical language and drawings, from the *algebraic system*, in which relationships between the properties of matter are expressed using formulas and graphs” (Talanquer, 2011, p.184). He also laments how there is an implicit assumption that the symbolic components of chemical language belong to the symbolic level while its more iconic components are associated with the particulate level (Talanquer, 2011). In other words, drawings of chemical ideas are implicitly assumed to depict what happens at the particulate level while chemical symbols and language are thought to represent only what happens at the symbolic level. This criticism is warranted, given how chemical educators make assumptions about students’ conceptual understanding of chemical ideas by routinely using the Johnstone Model.

In my perspective, the Johnstone Model is inadequate in its current form to describe all the representational levels students need to describe chemical bonds. For instance, the model leaves out the role of language in describing chemical bonds or the use of relevant examples to describe the bonds. Previous research into the sources of students’ difficulties when learning chemistry have pointed out how, unable to predict the structure of elements and compounds, students resorted to everyday expressions to predict chemical properties (Ben-Zvi, Eylon & Silberstein, 1988). The authors emphasized the importance of making the meaning of chemical symbols apparent to their students, finding it useful to emphasize the relationship between chemical symbolism and three distinct levels of descriptions of matter: the *macroscopic* (of the phenomena), the *atomic/molecular* (one single-particle), and the *multi-atomic* (many particles).

Ebenezer and Erickson (1996) similarly found the role of everyday language and experiences critical for Grade-11 chemistry students' conceptions of solubility phenomena. The authors, after studying the students' conceptions of solubility systems prior to classroom instruction on solution chemistry, raised three general issues regarding chemistry learning and teaching: first was the finding that students' everyday knowledge played critical role in shaping their understanding and interpretation of solution processes; second, there was a discrepancy between the meanings implied by the students' language and teacher's intended meanings for chemical materials through their use of chemical symbolism and language; and third, the students had tendency to extend their understanding of properties of materials at the macroscopic level to the particulate level. These findings have important implications for chemistry teaching and curricular design efforts.

For the reasons described above, and in light of other research showing students' lack of understanding the models and languages needed to represent and manipulate mathematical problems (Behr, Wachsmuth & Post, 1985; Post, Behr & Lesh,1986), and by extension chemical problems, this study uses *an amalgamated representational model* derived from the Johnstone Model in chemistry education and a model commonly used in the mathematics education field – The Lesh Translation Model. Figure 2.3 shows the Lesh translation model as is commonly used in mathematics education (Lesh, Cramer, Doerr, Post & Zawojewski, 2003). Further descriptions of the model follow.

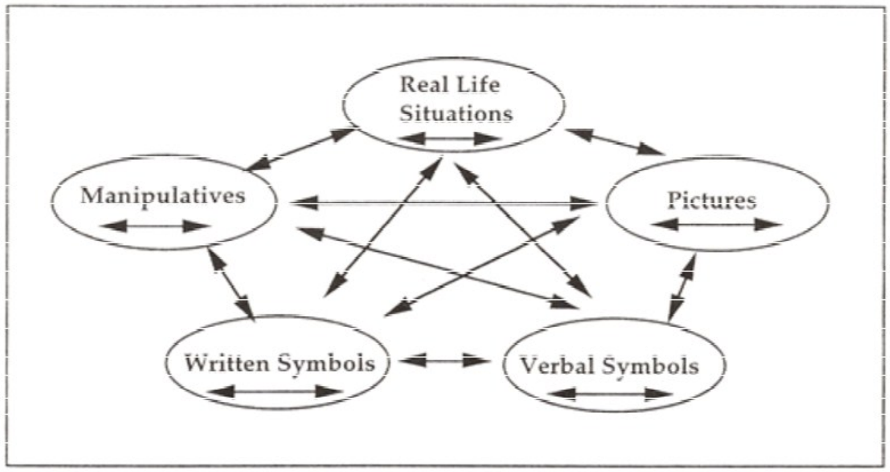


Figure 2.3. Lesh Translation Model (figure from Lesh, Cramer, Doerr, Post & Zawojewski, 2003)

As shown in Figure 2.3 the Lesh Translation Model (heretofore referred to as the Lesh Model) describes five contexts for representing mathematical ideas: pictorial representations, verbal symbols, written symbols, manipulatives, and real-life contexts. Similar to the Johnstone model, the Lesh model emphasizes the ability to facilely shift between the five representational levels as well as translations within the various modes of representations to make ideas meaningful to students. For example, the arrows connecting the different representations depict translations between the representations while the internal arrows indicate translations within representations.

The more fine-grained typology in the Lesh model provides more complexity than the Johnstone Model. This increased complexity can account for the role of language and everyday experiences in students' responses. However, the model, with its propositions and assumptions about how knowledge is obtained, needs to be refitted for chemistry education purposes. Thus I have combined the two models to account for disciplinary-criteria of how chemical knowledge is created. The result is amalgamated Johnstone-Lesh model (see Figure 2.4) with features from the two models re-mixed to create the new model.

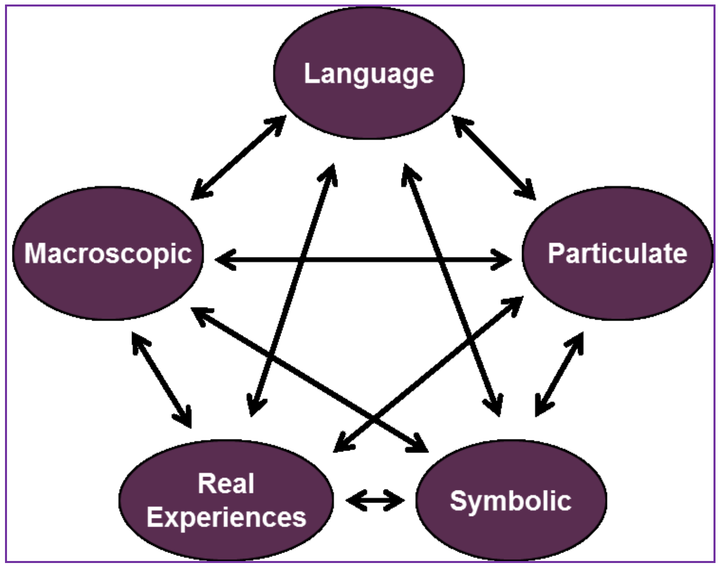


Figure 2.4 Proposed Johnstone-Lesh Model for the representation of chemical knowledge. The proposed model combines Johnstone's three representational levels with two representations from the Lesh Translation model from mathematics education.

In the new model (Figure 2.4) the particulate mode of the Johstone model replaces the pictorial mode of the Lesh model. The particulate-level is assumed to represent models that convey to us what happens at the atomic/molecular level. The symbolic-level of the Johnstone model replaces the written symbols mode of the Lesh model. This would account for both iconic and symbolic features in chemical equations. The "verbal symbol" mode of the Lesh model is reconstituted in the new model to represent the role of language in chemical understanding. The "manipulatives" mode of the Lesh model is replaced by Johnstone's macroscopic-level representations. Finally, the "real life situations" in the Lesh model is reconstituted as "real experiences" in the new mode.

The Johnstone-Lesh model shown in Figure 2.4 suggests chemical knowledge and understanding can be demonstrated through five different representational levels:

symbolic, particulate, macroscopic, real experiences, and through language use. The two new dimensions, in regards to chemistry, are real experiences and language element. Real experiences include our descriptive knowledge of chemical materials, gained through direct exposure (e.g., real life situational events) or indirect exposure (e.g., use of physical manipulatives and instruments). The language element would account for the critical role everyday language and language usage plays in shaping the students' conceptions of chemical ideas.

The representational forms described in the amalgamated Johnstone–Lesh model are not exclusive to each other, but rather interconnected (Figure 2.4). The challenge in chemistry teaching, however, has been students' inability to understand the connection between these representational forms and the need to facilely shift between them. This, then, appears to be a question of pedagogical approach. The prevalent approach in chemistry teaching often relies on symbolic representation of ionic bonds, with particulate representations of ionic bonds taught here and there.

For improved conceptual understanding, it is important to help students understand the connections between the representational levels in Figure 2.4. Therefore, a convenient way to explore students' abilities to facilely shift between the multiple representations when describing ionic bonds is to put them in situations that force them to verbalize their ideas about ionic bonding and to construct shared meaning of chemical bonds. The present study achieved this by putting students in structured cooperative learning groups that shared conceived understanding of chemical problems – situated events that forced the students to verbalize their thinking about ionic bonds (and thereby accounting for the role of language in their description of ionic bonds). The next chapter, chapter 3, provides further details of how this was achieved and outlines how the research was conducted and how the effects of cooperative learning groups on student understanding of ionic compounds was examined.

2.5. Chapter Summary

This chapter provided an overview of the literature informing the present study as well as its guiding theoretical frameworks. The literature on chemical misconceptions revealed students of all ages and educational levels hold common misconceptions about chemical ideas in all content areas and that misconceptions tend to be persistent and stable. One active area of research, and of particular interest to this work, was students' conceptions of ionic compounds. The emerging picture from the reviewed literature showed chemistry students having difficulty conceptualizing the nature of ionic bonds and often using alternative frameworks to describe the bonding within ionic compounds. More interestingly, students had multiple misconceptions about the nature of dissolving ionic solids, with many thinking salts and sugar react with water to form new molecular compounds or dissociate as neutral atoms or molecules. These findings have implication for how we should teach solution chemistry and more broadly the core area of chemical bonding. Using the symbolic interactionist perspective described in the foregoing pages, this study describes how cooperative inquiry-based pedagogies, specifically POGIL instruction, impact student understanding of the nature of dissolving ionic compounds in water. The next chapter provides details about the study's design, methods of data collection, and how the data was analyzed.

CHAPTER 3

Research Methods

"As observers and interpreters of the world, we are inextricably part of it … Thus it is always possible for there to be different, equally valid accounts from different perspectives"

Maxwell, 1992, p283

"If you want to understand the way people think about their world and how those definitions are formed you need to get close to them, to hear them talk and to observe them in their day-to-day lives"

Bogden and Biklen, 2003, p31

This chapter provides the context under which this research was conducted and details the data collection and analysis procedures. I will first provide an overarching view of the study research design in these opening remarks. The approach I have taken is a mixed methods approach in which I coupled qualitative data analysis to quantitative one-group pre–posttest analysis (Creswell, 2003). This is justified in that the quantitative one-group pre–posttest provides numerical evidence for the efficacy of the POGIL activities while the qualitative data provides interpretations of how group thinking influences students' representations of ionic compounds as well as cataloging the diverse ways in which students draw particulate representations of ionic compounds (Kern, Wood, Roehrig, &

Nyachwaya, 2010; Nyachwaya *et al*., 2011; Becker, Rasmussen, Sweeney, Wawro, Towns & Cole ,2012). Furthermore, the qualitative data provides rich context for analyzing classroom discourse and its influences on student learning.

Two of the three research questions (research question 1 and 2) are qualitative in nature. These questions attempt to describe how group thinking influences individual student learning and the effects of teacher-initiated discourse on student learning. Together, these two questions form the primary aims of the study. As I describe below, the main unit of analysis for the qualitative data was transcribed group dialogues during POGIL Activity. Classroom artifacts and field notes provided secondary vantage points. Findings from the qualitative analysis also informed the quantitative data analysis.

Research question 3 was mainly quantitative in nature though qualitative analysis was not necessarily absent from the analysis – for instance, I used qualitative themes developed from the data to quantitatively describe how POGIL activities influenced student learning. Figure 3.1 below shows the general scheme of the quantitative data.

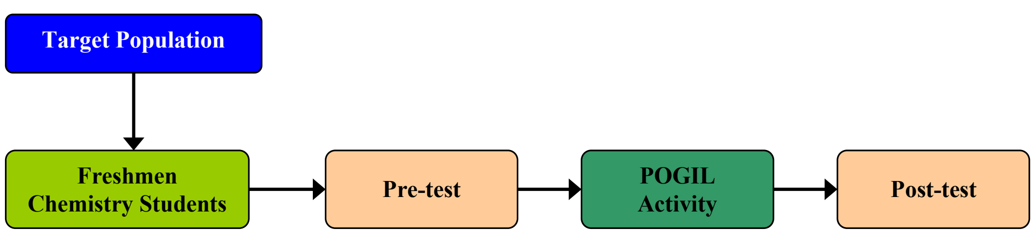


Figure 3.1. Pretest–posttest design proposed for the quantitative aspect of the proposed study

As can be seen in the figure, the main analysis in the quantitative section was pre-posttest measures of student achievement. Note there was no separate control group for this analysis. The use of a pre–posttest design without control group was justified since all students in the study received the POGIL intervention as a group. By measuring students' representational fluency of ionic compounds before and after experiencing the POGIL interventions, we were able to make inferences on its effect on student understanding and learning (Shaddy, 1986).

Qualitative and quantitative data collection and analysis occurred concurrently. Such an approach is described in the research literature as concurrent triangulation strategy (Creswell, 2003). Towns (2008) suggests that concurrent triangulation strategy in mixed methods approach "allows researchers to counteract biases or weaknesses in either qualitative or quantitative approaches and provides methodological triangulation" (p142). Thus the goal in concurrent triangulation approach, as was the case in this study, is to have the findings generated by each study confirm, converge, or corroborate each other. For instance, the data from research questions 1 and 2 (qualitative data) were used to corroborate or confirm findings from research question 3 (quantitative data). Greenbowe and Meltzer (2003) used similar approach of concurrent triangulation strategy to uncover the conceptual difficulties faced by college chemistry students studying calorimetry. Similarly Bridle and Yezierski (2012) used a quasi-experimental approach with primarily quantitative one-group pretest–posttest design to investigate the effectiveness of inquiry-based particulate modeling experience in improving students' conceptual understanding of phases of matter and change. The nature of the qualitative and quantitative procedures and the mechanism of data collection are further elaborated under the data collection and data analysis section page 16.

3.1. Research context and setting

The data for this study was collected in a first-semester freshman general chemistry class at a Mid-Western University campus in the United States. The course is designed for students desiring one or more years of chemistry and is typically taken by those intending to major in the sciences and engineering, as well as premedical health professionals. Topics covered included chemical formulas and equations, chemical reactions and energy, atomic and molecular structure, safe handling of chemicals and synthetic analytical techniques. Course pre-requisites included high school chemistry and college algebra or math proficiency as demonstrated by ACT Math or local University Math Replacement Test scores. The textbook used was Nivaldo Tro's Principals of Chemistry: A Molecular Approach, 2nd edition (Tro, 2011). The textbook included an online homework system, Mastering Chemistry, which the course instructor assigned to students regularly. Students met weekly for three hours of lecture, one hour of discussion, and three hours of lab. There were five unit tests and a comprehensive final exam.

The course instructor is a dedicated teacher committed to familiarizing students with the representations forms of chemistry throughout the course. The instructor had extensive experience with POGIL instructions, *e.g.*, served on the POGIL project leadership team and co-facilitated POGIL workshops in addition to using POGIL for several years. As such, the instructor was familiar with cooperative learning techniques and has over the years used varied active learning techniques as part of his/her instructional repertoire.

Students in the class often worked in small, cooperative groups. There were some variations from the typical cooperative learning groupings one would expect to see in traditional cooperative learning setting. For instance, the course instructor did not assign base groups or strive to achieve heterogeneity among the groups. Johnson, Johnson, and Smith (1991) and Heller and Hollabaugh (1992) previously reported heterogeneous cooperative groups with appropriate gender and ability mix appear to work best for college students. However, the course instructor in this case had more inclination towards ad hoc assignments of the groups.

Now that I have situated the study in context, allow me to describe the structure and organization of the remaining sections of the chapter. The next section describes the instructional unit used in the study and the nature of the POGIL activities. This is followed by a description of data sources, data collection and data analysis in that order.

3.2. Unit of instruction

The instructional unit for this study covered solution chemistry and occurred during the seventh week of the course. At this point of the course, students had learned about chemical nomenclature, writing and balancing chemical equations, stoichiometry, and the basics of solution chemistry. Based on our earlier research (Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011) and findings from the science education research with respect to student understanding of the particulate nature of matter (Gabel, 1999; Ben-Zvi, Eylon, & Silberstein, 1987; Griffiths & Preston, 1992), the instructional unit had four components. These included (a) providing relevance for the content being addressed, (b) linking for students explicitly macroscopic, particulate, and symbolic representations, (c) providing physical manipulatives that make the particulate ideas concrete, and (d) providing compare and contrast examples to solidify student's understandings of the different chemical bonding modes. Activities dealing with these features were linked in a logical manner, starting with macroscopic demonstrations (ChemActivity 1, Figure 3.2 (POGIL activities are called ChemActivities)) followed by particulate and symbolic representations of dissolved compounds (ChemActivity 2, Figure 3.3), and a subsequent activity on electrical conductivity (ChemActivity 3, Figure 3.4). Further description of each of these activities follows.

The first of the POGIL activities, ChemActivity 1, was essentially instructor-led macroscopic demonstration of what happens to materials dissolved in water (see Figure 3.2). Upon observing the dissolution of NaCl and methanol in water, the students were asked to describe, in their own words, the appearance of the chemicals before and after the addition of the water.

POGIL ChemActivity 1: what happens to chemical compounds placed in water?

3D Molecular Design Kit Activity. *You will be provided with a kit that has the following contents:16-18 water (H_2O) molecules,4 sodium ions (Na^+), 4 chloride ions (Cl^-), and a molecule of methanol (CH_3OH). All atoms are magnetized although the magnitude of the charges is not reflected in the model. Your group will also receive a tray to place the atoms, ions, and molecules. You will use this molecular kit to investigate what happens to compounds when we put them in water*

Activity 1: What do we observe when ionic and molecular compounds are put in water?

1. Your instructor will demonstrate the dissolution of sodium chloride (NaCl) and methanol (CH_3OH) in water. Describe, in your own words, the appearance of chemicals before and after the addition of the chemicals in water.
    a. Verbal description of sodium chloride (NaCl) before and after adding it to water
    b. Verbal description of methanol (CH_3OH) before and after adding it to water

Figure 3.2. Description of activity POGIL ChemActivity 1 of the POGIL activity series. This particular activity asked students to observe and describe verbally what happens when ionic and molecular compounds are stirred in water.

There was often instructor-led whole-class discussion accompanying ChemActivity 1, often with the teacher making direct links between students' every day experiences and the solubility of chemical compounds in water or providing chemical reasoning and justifications for observed chemical behavior. The following is an exemplar of such discussion:

Teacher: *Okay, I'm going to have you look back at the front. What I'm going to do for you is activity one. Activity 1 is essentially a macroscopic observation of dissolving materials in water …*

Teacher: *Let's start with a little observation. I have this chemical here. How would you describe it?*

Class: *Salt. Crystalline*

Teacher: *What kind of salt?*

Class: *Table salt*

Teacher: *NaCl. Also chemically called…?*

Class: *Sodium chloride.*

Teacher: *We have crystalline, table salt, sodium chloride. If I were to look at this under a microscope I'd definitely see nice little square type crystals.*

Teacher: *I'm going to take some of these crystals and put them in my container. I'm going to add some water. At some point in your lifetime you've probably done this with table salt. You've taken salt and add water to it [Teacher stirring salt in water].*

Teacher: *How do you describe what happens?*

This particular discussion continued awhile, with the teacher using Socratic method to probe students understanding of chemical bonding theories and making links between particulate, macroscopic and symbolic representations. Similar discussions often ensued following ChemActivity 1.

The second activity (ChemActivity 2, Figure 3.3) of the series asked the students to draw particulate images of NaCl and methanol before and after they are dissolved in water and subsequently to, based on their particulate drawings, select a correct multiple-choice option among given symbolic equations showing dissolution of NaCl and methanol in water. Figure 3.3 shows ChemActivity 2. Both ionic (NaCl) and molecular (methanol) were used here to help the student understand the differences in chemical bonding modes. Additionally, the options in the multiple choice question were based on common student-generated errors we previously noted while using an open-ended drawing instrument we developed as a tool to examine college student's particulate level understanding of chemical reactions (Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011) – for instance, errors related to subscript use, states of matter, the use of neutral-ion pairs for dissolving ionic solids in water, etc. The study by Naah and Sanger (2012) similarly tabulated many of these student-generated errors.

POGIL ChemActivity 2: what happens to chemical compounds placed in water?

***DIRECTIONS**:* Obtain a matrix of sodium chloride (NaCl) and all of the water molecules from your 3D Molecular Design Kit. Diagram what you see then mix the compounds in your tray by using your hands to break up and rearrange any particles that are magnetically attracted to one another.

1. In the space below, draw a diagram that represents what happened to the sodium chloride (NaCl) matrix when placed in water. Make sure to provide a legend for your drawing or write appropriate symbols inside each atom core.

Before Mixing	***After Mixing***

2. Based on your particulate diagram, which of the following balanced equations shows what happens to sodium chloride (NaCl) placed in water?
   a. NaCl *(s)* → Na *(aq)* + Cl *(aq)*
   b. 2NaCl *(s)* + H_2O *(l)* → 2HCl *(aq)* + Na_2O*(aq)*
   c. NaCl *(s)* → Na^+*(aq)* + Cl^-*(aq)*
   d. NaCl *(s)* → Na^+*(s)* + Cl_2^-*(s)*
   e. NaCl *(s)* → Na^+*(s)* + Cl^-*(s)*

Figure 3.3. Description of POGIL ChemActivity 2 of the POGIL activity series. This particular activity asked students to observe and describe verbally what happens when ionic and molecular compounds are stirred in water.

The third activity in the series (ChemActivity 3) was designed to teach the students about the differences between ionic and covalent bonds through analysis of the conductivity of ionic and molecular compounds. Figure 3.4 shows ChemActivity 3 (the full activity, 1 – 3, is shown in appendix B). As can be seen in the figure, students were first asked to predict the conductivity of sodium iodide (NaI) and sucrose ($C_{12}H_{22}O_{12}$) and subsequently observed the course instructor demonstrate the conductivity of water before and after the addition of NaCl and methanol (Figure 3.4). Following the instructor's macroscopic demonstration, students were given tabular data showing conductivity values of several ionic and molecular compounds and asked to answer series of guided questions about ionic and molecular compounds (Figure 3.4).

POGIL ChemActivity 3: What happens to the conductivity of water when compounds are dissolved in it?

1. Based on your observations in Activity 1 and 2, ***predict*** whether or not the following compound aqueous solutions would conduct electricity. In your response, ***state clearly this compound aqueous solution "will" or "will not" conduct*** and provide short explanation for your reasoning.

    a. Solid sodium iodide (NaI) dissolved in water:

    b. Solid sucrose ($C_{12}H_{22}O_{12}$) dissolved in water:

Please do not go onto the rest of the activity until you have made your predictions!!!

Information

The conductance of aqueous solutions can be measured using a devise that displays conductivity values. There are many different devices used for measuring conductivity. One type of device has lights (LEDs) that light up when a solution conducts electricity. The number of lit LEDs is proportional to the conductivity of the ions in the dissolved solution.

2. *Your instructor is going to demonstrate the conductivity of water before and after the addition of sodium chloride (NaCl). Describe your observations in the space below.*

Conductivity before addition of NaCl ***Conductivity after addition of NaCl***

Critical Thinking Questions

Refer to the information in Table 1 below to answer the following questions

Table 1: Conductivity values of several chemical compounds in water.

Experiment #	**Aqueous Solution (M = mol/L)**	**Observation**	**Conductivity in Water (# of LEDs lighting up)**
1	0.1 M sodium chloride (NaCl)	Clear, colorless solution	2
2	0.2 M sodium chloride (NaCl)	Clear, colorless solution	4
5	0.1 M sodium sulfate (Na_2SO_4)	Clear, colorless solution	3
6	0.2 M sodium sulfate (Na_2SO_4)	Clear, colorless solution	6
8	Deionized water (H_2O)	Clear, colorless solution	negligible
9	0.1 M sucrose ($C_{12}H_{22}O_{12}$)	Clear, colorless solution	negligible
10	0.1 M methanol (CH_3CH_2OH)	Clear, colorless solution	negligible

3. Categorize the compounds listed above based on their solution conductivity (see Table 1).

4. Based on your response above, what type of compounds conduct electricity when dissolved in water?
5. ***According to the data in Table 1, what is conductivity of (in LEDs)
   a. 0.1 M sodium chloride (NaCl)? ________________ LEDs
   b. 0.2 M sodium chloride (NaCl)? ________________ LEDs
   c. Explain why the conductivity values of 0.1 M and 0.2 M solutions of sodium chloride (NaCl) are different?
6. Consider again the data in Table 1.
   a. What is the conductivity of 0.1 M sodium sulfate (Na_2SO_4) ____________________ (LEDs)
   b. Calculate the ion concentration in 0.1 M NaCl and 0.1 M Na_2SO_4. Describe how this helps explain the conductivity differences between the two solutions.
   c. In the space below, draw a diagram that represents what happens to solid sodium sulfate (Na_2SO_4) when it is placed in water. Make sure to provide a legend for your drawing or write appropriate chemical symbols inside each atom core.

Figure 3.4. POGIL ChemActivity 3 on chemical conductivity. This activity compared and contrasted the chemical conductivity of ionic and molecular compounds in an effort to help the students understand the differences between bonding modes

To make concrete the differences in chemical bonding models, and more importantly how the differences account for observable chemical properties, the activity utilized physical manipulatives in the form of a molecular model kit from 3D Molecular Designs (www.3dmolecuardesigns.com). The kit contained a lattice of sodium chloride, 18 water molecules, 1 molecule of methanol, and a molecule of methane (see Figure 3.5 for image of the NaCl lattice and water molecules). All atoms in polar compounds in the kit were magnetized although the magnitude of the charges is not reflected in the model — e.g., some particles have full positive charge whereas others have partial charge, however all atoms are equally magnetized in this model, including ionic compounds (3D Molecular Design, 2012). Students used this molecular kit in both ChemActivity 2 and 3 to help them visualize what is happening at the particulate level.

Magnetized NaCl Lattice Magnetic Water Molecules

Figure 3.5. Picture of the physical manipulatives used in the study. The image on the left showed images of NaCl lattice; the image on the right is that of the water molecules.

Throughout the activity the students worked in small groups of 3 to 4 members. They also self-assigned themselves to cooperative roles. Figure 3.6 shows a handout the students received during the first week of classes when they were introduced to POGIL pedagogy. The handout described the quality indicators for the different roles student play and the associated process skills they are expected to learn. Detailed handouts of each role were also given to the students in the first week of classes.

Quality Indicators for POGIL Roles

Facilitator
- The group begins promptly
- The group stays on task, progressing through the activity in a timely manner
- All members of the group are participating

Spokes Person
- Seeks group input before consulting teacher or other groups
- All members feel satisfied that their issues have been addressed
- Articulates questions and responses well

Quality Control
- Any individual sample collected should accurately demonstrate the groups' understanding
- Regularly checks that group members' answers are consistent (not identical)
- Encourages individuals to make sure answers are thorough (i.e. showing work)

Process Analyst
- Reports to group regarding group performance at least one time during the activity and at the end
- Provides insightful and positive feedback on how the group is working
- Completes the process questions report form if directed

Figure 3.6. Description of POGIL roles in student groups (from www.pogil.org and course instructor)

3.3. Data sources, collection and analysis

3.3.1. Data sources

Multiple data sources were used in this study including pre-posttests items, class exams, student particulate drawings, participant worksheets and audio-recorded group conversations. Each of these items is further described in a greater detail in the data collection and data analyses sections. A multidimensional perspective of data collection, as used for this study, is necessitated by the complex and multidimensional nature of educational settings (Salomon, 1991; Shulman, 1986; Singer, Tal & Wu, 2003).

3.3.2. Data collection techniques

Table 3.1 summarizes the methodologies and methods of data collection and analysis. In the table, the research questions in the study are aligned with the research paradigm used to address them (qualitative or quantitative) and a description of the research methodology and methods of data collection and analysis is shown. Further descriptions follow under separate headings for the qualitative and quantitative data.

Table 3.1
Overview of research paradigms, methodologies and methods of data collection

	Research Paradigm	
	Qualitative	**Quantitative**
Research Questions Addressed	Research question 1: How does group thinking during a cooperative inquiry-based activity on chemical bonding influence college students' conceptions of ionic compounds in solution? Research question 2: How do teacher's practical moves influence students' meaning making processes and sociochemical norms?	• Research Question 3: How do cooperative inquiry-based pedagogies, namely POGIL pedagogy, impact student understanding of the nature of ionic compounds in solution?
Methodology	• Discourse/Episode analysis	• Statistical analysis
Methods of Data Collection	• Audio recorded group conversations • Participant worksheets • Student particulate drawings (drawings on pre-posttest measures)	• Pre-test assessment • Post-test assessment • Midterm exams
Data Analysis	• Transcripts of audio-recorded group conversations • Document analysis (researcher notes, participant notes)	• Descriptive statistics • *t*-test Analysis
Narrative form	• Theoretical models of representational fluency • Thematic description of group conversations	• Detailed discussion of numerical evidence (or lack there off) of the efficacy of POGIL instructions

3.3.3. Qualitative data collection techniques

There were three sources of qualitative data: 1) audio-recorded conversations of the ten autonomous groups completing the POGIL activitiy; 2) written classroom artifacts (worksheets, group reports, exam responses) from the POGIL activity, and; 3) researcher observations and field notes. The following paragraphs describe the process in greater detail.

3.3.3.1. Group selection and make-up

The observed class had 20 cooperative groups with 3 to 4 student members. Because the groups self-organized organically throughout the course, it was not possible to predetermine which groups to select. All groups have previously consented to participate in the study and on the day of the recording all were asked if they will be willing to be audio-recorded and their interactions closely monitored. Thirteen of the twenty groups consented to the recording. Three of the 13 recordings did not materialize due to technological issues that rendered them unusable. Thus the final sample, consisting of recordings for 10 different autonomous groups, was a convenient sample (Creswell, 2003). However, while convenience may have been the driving force for the group selection at the time of the data collection, group and class comparison during data analysis suggested the groups were representative of the whole class without extreme or unusual characteristics (e.g., comparable pre-posttest scores).

Table 3.2 below describes the gender make-up, meeting times, and the specific role(s) each student played in their respective groups. Recordings in the study were completed during three discussion sessions led by the course instructor. In Table 3.2, and in the rest of this dissertation, groups are labeled as follows. Each group has a number (1, 2, or 3) and a letter (A, B, C, or D) assigned to them. The number refers to the session the students were in (the first, second, or third) while the letter identifies the specific group within each discussion session. Thus 3B refers to group B who met during the 3rd discussion session while 1D will refer to group D who met during the 1st session.

Table 3.2
Group demographics and individual roles during POGIL Activities. Groups met for three different sessions as follows: group 1 (1A-1D) met for session 1, group 2 (2A-2D) met for session 2, group 3 (3A and 3B) for session 3. S in the table refers to students.

Group	Gender Make-Up		Role Played in the POGIL Activity
1A	*S1*	*Female*	Facilitator
	S2	*Female*	Spokesperson
	S3	*Female*	Quality control
	S4	*Female*	Process analyst
1B	*S1*	*Female*	Facilitator
	S2	*Female*	Spokesperson
	S3	*Female*	Quality control
1C	*S1*	*Female*	Facilitator
	S2	*Female*	Spokesperson
	S3	*Male*	Quality control
1D	*S1*	*Female*	Facilitator
	S2	*Male*	Spokesperson
	S3	*Female*	Quality control
	S4	*Male*	Process analyst
2A	*S1*	*Female*	Facilitator
	S2	*Female*	Spokesperson
	S3	*Female*	Quality control
2B	*S1*	*Male*	Facilitator
	S2	*Male*	Spokesperson
	S3	*Male*	Quality control
2C	*S1*	*Female*	Facilitator
	S2	*Female*	Spokesperson
	S3	*Male*	Quality control
2D	*S1*	*Male*	Facilitator
	S2	*Male*	Spokesperson
	S3	*Male*	Quality control
	S4	*Male*	Process analyst
3A	*S1*	*Male*	Facilitator
	S2	*Male*	Spokesperson
	S3	*Male*	Quality control
3B	*S1*	*Female*	Facilitator
	S2	*Female*	Spokesperson
	S3	*Female*	Quality control

3.3.3.2. Transcripts of audio-recorded group conversations

As mentioned above group conversations recorded during discussion sessions were one of the primary sources of data collection. Recorded group conversations were transcribed verbatim by trained undergraduate students at STEM Education Center at the University of Minnesota. Once I received these transcripts, I doubled checked them for accuracy and precision and returned to the original recordings several occasions to re-listen and clarify what is meant by the students (Rubin & Rubin, 2005). These transcripts served as the primary data source while observational notes and classroom artifacts provided a second vantage point.

3.3.4. Quantitative data collection techniques

The quantitative data came from questions in pre-posttest measures of student achievement. There were two kinds of pretest items, early pretest and immediate pretest items, and three kinds of post-test items administered at different time points after students successfully completed the POGIL activities. Table 3.3 shows the time line and the format of both pre- and posttest items while further description of each test follows in subsequent paragraphs.

Table 3.3
Timeline and format of pre-posttest measures of student achievement

Measure	Timeline	Test Format	Page Information
Early pre-test	First day of classes	Open-ended items	61
Immediate pre-test	The day before the POGIL activities	Multiple-choice	62
Immediate post-test	The day after the POGIL activities	Multiple-choice	62
Delayed posttest - Midterm	Two weeks after POGIL activities	Open-ended and multiple-choice	63
Delayed posttest – Final Exam	Eight weeks after POGIL activities	Open-ended items	63

3.3.4.1. Early pretest items

Figure 3.7 shows the early pretest items which consisted of three chemicals (KI, $AgNO_3$, $CaCl_2$) and an open-ended item question asking students to describe, in words, what happened to solid potassium iodide (KI) crystals dissolved in water. With respect to $AgNO_3$ and $CaCl_2$, students were asked to balance the chemical equation showing the reaction of these two chemicals to form silver chloride (AgCl) and aqueous calcium nitrate ($Ca(NO_3)_2$) and to draw particular diagrams of this reaction (Figure 3.7). This item was previously used to investigate students' particulate nature of matter understanding (Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011).

Pre-Assessment Test

This is an instrument developed to test your present knowledge about some scientific concepts taught in chemistry courses. The results of this test would have no effect on your grade in your chemistry class. Results will only be used for research purposes and for improving the chemistry course you are taking this semester.

1. Suppose you placed a spoonful of solid potassium iodide (KI) in water (H_2O) and stirred until the crystals disappear.
   a. Please **explain in words** what happened when the KI crystals disappeared in water
   b. **Write** a balanced chemical equation showing what happened
   c. In the space below, draw diagrams that represent what you think you might see if you were able to see the atoms, molecules, and ions present in the chemical equation above. Remember to draw the correct number of atoms, molecules, and ions in each reactant and each product.

2. When a solution of calcium chloride ($CaCl_2$) is mixed with a solution of silver nitrate ($AgNO_3$), a white solid forms. The unbalanced chemical equation for this reaction is shown below. The solid that forms is silver chloride (AgCl) and can be separated from the liquid by filtration.

   $$\_\_\_\_ CaCl_2(aq) + \_\_\_\_ AgNO_3(aq) \rightarrow \_\_\_\_ Ca(NO_3)_2(aq) + \_\_\_\_ AgCl(s)$$

   a. Write the appropriate numbers in the blanks to balance the chemical equation.
   b. In the space below, draw diagrams that represent what you think you might see if you were able to see the atoms, molecules, and ions present in the chemical equation above. Remember to draw the correct number of atoms, molecules, and ions in each reactant and each product.

Figure 3.7. Items used in early pretest assessment administered during the first day of classes

3.3.4.2. Immediate pre-posttest items

The second pretest items were part of a cluster of six questions administered as immediate pre-posttest items a day before and after exposure to the POGIL activities. Table 3.4 shows these immediate pre-posttest questions. The immediate pretest items (Table 3.4) were the ionic solids potassium sulfate (K_2SO_4), magnesium nitrate ($Mg(NO_3)_2$) and calcium chloride ($CaCl_2$). The immediate posttest items (Table 3.4) were the sodium salts of sulfate (Na_2SO_4), chloride (NaCl) and iodide (NaI). These items were isomorphic structurally and contained common salts including household salts (i.e., table salts). Other salts, such as magnesium bromide ($MgBr_2$), were included in the delayed-posttest assessment as described below.

Table 3.4
Immediate pre-post items used to assess student conceptions of ionic solids dissolved in water.

PROMPT QUESTION	PRETEST ITEMS	POSTTEST ITEMS
Which of the following balanced equation shows what happens when solid [compound] is dissolved in water?	○ K_2SO_4	○ Na_2SO_4
	○ $Mg(NO_3)_2$	○ NaCl
	○ $CaCl_2$	○ NaI

The immediate pre-posttest questions assessed student understanding of what happens to dissolved ionic solids *at the symbolic level* as students selected from provided multiple choice options the correct balanced equation for dissolving ionic solids in water. Figure 3.8 shows sample immediate pre-posttest questions. The sample pretest question in Figure 3.8 asked students to select the correct multiple-choice option showing what happens to solid potassium sulfate (K_2SO_4) placed in water. Similarly, the sample post-assessment question asked the students to select the correct equation showing what happens to sodium iodide (NaI) placed in water.

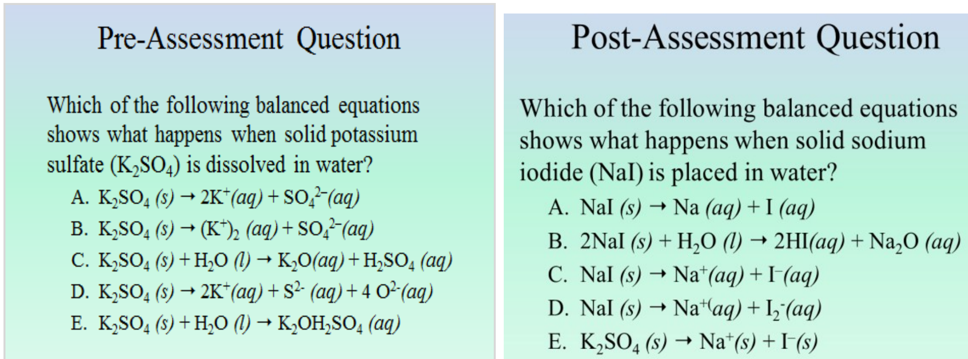


Figure 3.8. Sample immediate pre-post POGIL activity questions. The figure on the left shows sample immediate pretest question; the figure on the right shows sample immediate posttest question. The pre-post assessment questions were administered a day before and after the day the POGIL activities.

3.3.4.3. Delayed posttest measures: midterm and final exam items

In addition to the immediate pre-posttest items described above, an open-ended item and a multiple-choice item were embedded into the course's midterm and final exams, administered about two and eight weeks after completion of the POGIL activities respectively. Figure 3.9 shows these delayed-posttest items. The first midterm posttest question directed students to generate before and after particulate diagrams of calcium nitrate ($Ca(NO_3)_2$) dissolved in water. The second midterm posttest item was a multiple-choice symbolic-level question about the dissolution of magnesium bromide ($MgBr_2$). The posttest item in the final exam, aqueous $CaCl_2$, allowed direct comparison of this same item which was administered as part of the early pretest data given during the first day of classes.

Midterm Exam Posttest items

1. **<u>Open-ended item</u>**
   In the space below, draw a diagram that represents what happens to a matrix of solid calcium carbonate ($CaCO_3$) and liquid water (H_2O) before and after mixing. Make sure to provide a legend for your drawing or write appropriate symbols inside each atom core.
2. **<u>Multiple-Choice item</u>**
Which of the following balanced equations shows what happens when solid magnesium bromide MgBr2 is dissolved in water?

a. $MgBr_2(s) \rightarrow Mg^{2+}(aq) + 2Br^{-}(aq)$ b. $MgBr_2(s) + H_2O(l) \rightarrow 2HBr(aq) + MgO(aq)$ c. $MgBr_2(s) \rightarrow Mg^{+2}(aq) + Br_2^{-}(aq)$ d. $MgBr_2(s) \rightarrow Mg(aq) + Br_2(aq)$
Final Exam Posttest item 3. When a solution of calcium chloride ($CaCl_2$) is mixed with a solution of silver nitrate ($AgNO_3$), a white solid forms. The unbalanced chemical equation for this reaction is shown below. The solid that forms is silver chloride (AgCl) and can be separated from the liquid by filtration. ____ $HCl(aq)$ + ____ $CaCO_3(s)$ → ___$CaCl_2(aq)$ + ___ $H_2O(l)$ + ___$CO_2(g)$ a. Write the appropriate numbers in the blanks to balance the chemical equation. b. In the space below, draw diagrams that represent what you think you might see if you were able to see the atoms, molecules, and ions present in the chemical equation above. Remember to draw the correct number of atoms, molecules, and ions in each reactant and each product.

Figure 3.9. Delayed-posttest items embedded into midterm and final exam tests. In the final exam, only the aqueous $CaCl_2$ was used for analysis to measure retention effect.

3.4. Qualitative data analysis

3.4.1. Identification and analysis of sociochemical norms

The first research question of the study addressed the question of *how group thinking during a cooperative inquiry-based activity on chemical bonding influence college students' conceptions of ionic compounds in solution*. To answer this question, I developed a coding scheme to examine classroom discourse and how group thinking influences individual student learning. As I described in chapter one, the structure of the POGIL activities forces students to verbalize their thinking, discuss particulate and symbolic representations of ionic and molecular compounds, and make sense of chemical ideas. The goal, therefore, is to analyze how these social interactions influence the ways in which students develop personal understandings and how the group constitutes meaning of chemical bonding theories, including their ability to link particulate understandings to symbolic representations. Recall from chapter 2 that the term sociochemical norms is used to describe the social interactions that regulate classroom discourse and social norms in the field of chemistry.

3.4.2. Development and use of coding scheme

Given the dialogical nature of group discussions in POGIL activities, their transcribed dialogues served as a point of departure for data analysis. The use of episodes, or group's transcribed conversation, as a unit of analysis for classroom interactions has a long precedence in educational research (*e.g.*, see Smith and Meux, 1970; Hollabaugh, 1995). For the purposes of this study, episode boundaries are determined by shifts in what is discussed – e.g., the initiation of a new topic or new aspects of the same topic such as a shift from a discussion of ionic compounds to one about molecular compounds.

Using the episodes as unit of analysis, I looked for specific practices within and across the groups to identify sociochemical norms that might indicate influences of group thinking on individual understandings. An idea was considered to have become normative if it was used consistently as a chemical justification by the different autonomous groups in the study or initiated in a whole class discussion in different class meetings. Further refinement of these guidelines resulted the coding scheme and set criteria shown in Table 3.5. There were three codes: 1) GNC, or group negotiated criteria, 2) AGC, or across group-negotiated criteria, and 3) SST, shifts in student thinking.

Table 3.5
Coding scheme and criteria for data analysis

Code* #	Criteria	Explanation
GNC	Student groups negotiate and develop a criterion for what counts as acceptable justification for a chemical phenomenon (e.g., the dissolution of ionic compounds)	Code for group constitution of meaning
AGC	• Different autonomous groups develop and use similar criteria to explain the same chemical phenomenon • Different groups use the same criterion as justification for different topics	Code for a way of thinking becoming normative in class culture
SST	*shifts in individual student thinking* brought about by opposing viewpoints or new information contradicting their initial position	Code for evidence of sociochemical norms influencing individual understandings

**GNC = Group Negotiated Criteria; AGC = Across Group/Topic Criteria; SST = Shifts in Student Thinking*

The first code in Table 3.5, GNC, was used to code for statements indicating group constitution of meaning – that is, the code was used when it was observed that student groups were negotiating and developing criteria for what counts as acceptable justification for a chemical phenomenon (Table 3.5), such as the dissolution of ionic compounds in water or the electrical conductivity of chemical compounds. The second code, AGC, was used to tag statements that indicated a particular thinking became normative in small group or whole class discussions. Statements coded as AGC needed to meet one of two criteria or both in order to be coded as AGC (Table 3.5): (1) different autonomous groups developed and used similar criteria to explain the same chemical phenomenon; and/or (2) different groups used the same criterion as justification for different topics (Table 3.5). The last code, SST, was used to tag statements indicating shifts in student thinking brought about by group conversations.

Once the above codes were developed, I used them as follows. First, transcripts were segmented into episodes (again, episode boundaries were determined by shifts in what is discussed – e.g., the initiation of a new topic or new aspects of the same topic such as a shift from a discussion of ionic compounds to one about molecular compounds). Secondly, the appropriate codes were entered for each of the sequentially numbered individual statements that make up an episode. Let me provide an example to illustrate code usage.

3.4.3. An example of coded and delineated group dialogue

The following coded and delineated episode from Group 1A (see Figure 3.10) illustrates how the codes were used (I will return to this particular episode later in chapter 4). In this and in other episodes, the data is organized in a column format in such that group dialogue is shown first followed by statement identification (codes) and short comments or interpretations. Lines in the dialogue are numbered sequentially for ease of reference (the code LN refers to the specific line in a dialogue, for example, LN6 refers to line 6 in a given dialogue). In the example shown in Figure 3.10 below, Group 1A was attempting to justify their response of which balanced chemical equation was in agreement with their particulate drawing of NaCl dissolved in water.

Directions: Based on your particulate diagrams, which of the following balanced equations shows what happens to sodium chloride (NaCl) placed in water?

a. NaCl *(s)* → Na *(aq)* + Cl *(aq)*
b. 2NaCl *(s)* + H_2O *(l)* → 2HCl *(aq)* + Na_2O*(aq)*
c. NaCl *(s)* → Na^+*(aq)* + Cl^-*(aq)*
d. NaCl *(s)* → Na^+*(s)* + Cl_2^-*(s)*
e. NaCl *(s)* → Na^+*(s)* + Cl^-*(s)*

	Dialogue	Code	Comments/Interpretations
1	S1: So the water didn't change [*points to the molecular model of water in their tray]*, so the water goes with … so it's not A. Are they [*pointing to Na and Cl in their drawing]* aqueous?	GNC AGC*	*Initiating move; S1 proposes justification (water didn't change) and asks for clarification (are they aqueous)*
2	S2: Yeah, they're aqueous	GNC	*Confirmatory response statement*
3	S3: So, wouldn't it be C? Those are the only aqueous	GNC	*Consensus checking statement*
4	S4: Yeah. That's what I'd think	GNC	*Acknowledgement statement*
5	S2: They're still ions	GNC AGC*	*S2 proposes a new criteria (needs to be ions)*
6	S1: So a plus and negative would be good. And its balanced. Good. So now activity three [*group moves on to the next activity*].	GNC SST	*This is coded both GNC and SST because S1 did not initially propose +/- as a criterion but shifts thinking after S2 proposed ions as a criterion*

*AGC code can only be used if comparing the same episode for more than two groups or different episodes

Figure 3.10. Group 1A's dialogue on choosing correct equation to represent the dissolution of sodium chloride (NaCl) in water.

In the initiating move in the episode in Figure 3.10, *S1* provides justification for why the answer can't be A ("water didn't change", LN1) and then proceeded to seek confirmation ("Is it aqueous" LN1). Because these statement indicate group construction of meaning, they were coded as GNC. Obviously confirmatory statements require input from other members in the group and we see *S2* providing confirmatory statement in line 2 ("Yeah, it's aqueous"). Statements in lines 3-6 similarly contained group discussion (GNC) of why a particular option is not feasible or why option C is the correct option. All of these statements are of particular type (confirmatory seeking/response statements, acknowledgement, justification statements and consensus checking statements) and indicate group negotiation and constitution of meaning.

The statement by *S1* in line 6 is coded as SST (shift in student thinking) because *S1* did not initially propose pluses and negatives as a criterion for ionic compounds in solution but shifts thinking after *S2* proposed ions as a criterion. Several of the statements in Figure 3.10 were coded as AGC (across group criterion) because other groups in the study used the terms aqueous, ions, and chemical change as criterion for choosing the correct multiple-choice option. These ideas became normative across the groups and were thus coded as AGC. Similar analysis was completed for the rest of the episodes and groups.

3.4.4. Further refinement of the codes

The further identification of several statements types in the group's dialogues made the coding process more manageable. Table 3.6 shows the nature of these statement types. In the table, the original codes (GNC, AGC, and SST) are shown on the top, followed by the statement types. These statements were solely used to identify the major codes.

Table 3.6
Statement types that helped application of code criteria

GNC	AGC	SST
• Dialogue initiating and response statements • Confirmatory statement • Follow-up statements • Consensus checking statements • Acknowledgement and supporting statements • Summary, request, and clarifying questions	• similar themes, ideas, and words repeated across groups • Similar ideas, themes, and words repeatedly used by the same group as justification for different topics (e.g., the idea of "chemical change" used to explain different topics)	• Skeptical and challenging question that shift to acceptance • Out right admission of change in ideas [e.g., I totally did that wrong the other day!] • Request of information and indication of change following information acceptance

3.4.5. Using literature to develop the codes

Two of the above codes in Table 3.5, AGC and SST, were modifications of criteria used in studies conducted by colleagues Cole, Becker, Towns, Sweeney, Wawro and Rasmussen (2011) and Becker, Rasmussen, Sweeney, Wawro, Towns and Cole (2012) for analysis of classroom chemistry practices and sociochemical norms, respectively (see chapter two for further discussion of their studies). In their analyses, these researchers used Toulman analysis (1958) to develop argumentation logs and subsequently used three criteria to identify normative ideas. Criterion 3 of these earlier studies identified ideas as normative "when [such] ideas are repeatedly used as a justification for different claims on different days" (Becker, Rasmussen, Sweeney, Wawro, Towns & Cole, 2012, p.6) while their criterion 2 considered an idea normative if it "shifts position in subsequent arguments indicating knowledge acquisition (*e.g.,* claim shifted to data)" (Becker, Rasmussen, Sweeney, Wawro, Towns & Cole, 2012, p.6).

In this study, Toulman argumentation model was not used and, unlike the Cole-Becker studies, ideas were considered to have become normative not only when it was repeatedly used as justification *for different claims on different days* but also when different autonomous groups developed and used *similar arguments on the same chemical phenomenon* regardless of the distance in time (code AGC, Table 3.5). Similarly, because Toulman analysis was not used, we could not have used criterion 2 of these earlier studies in which an idea was considered to have become normative if it shifted in position – for example, from claims to warrants in the Toulman tradition. In this research, we looked for patterns indicating *shifts in individual student thinking* brought about by opposing viewpoints or new information contradicting their initial position (code SST, Table 3.5). This approach is more interpretive in nature and uses the constant comparison approach of Corbin and Strauss (2008) for qualitative data analysis.

3.5. Establishing inter-rater reliability

Upon agreement on the coding scheme, two researchers coded together an episode from one of the groups (Group 1B) and proceeded to code a second portion individually. These researchers then compared their results to establish consistency of code use. Inter-rater reliability based on percent agreement was at 91.7%. Following this initial coding event, other members of the research team coded portions of groups 1B and 2A episodes. Inter-rater reliability was again established. Subsequently, I coded the rest of the data, with ongoing discussion and dialogue with other research members. All disagreements were resolved through discussion.

3.6. Analysis of teacher-initiated classroom discourse

Analysis of discourse conversations involving the course instructor and student groups helped answer the second research question of *how does teacher's practical moves influence students' meaning making processes and sociochemical norms.* I looked for evidence of teacher-initiated discourse and how the teacher's practical moves influenced student dialogue. Figure 3.11 shows an example of a raw data from Group 1D in which the group is discussing the dissolution of sodium chloride in water. The group chose option B, in which a metal oxide and an acid forms, as their option. The course instructor (T in the conversation in Figure 3.11) joins the group's dialogue and a discourse ensues (the conversation starts at line 7).

	Dialogue
7	T: Did you observe this? Did you see the Na bonding to an oxygen and a Cl bonding to an H?
8	S1: No, we saw the water stay together
9	T: The water stayed together. So, does B support that?
10	S1: No, it's saying that it all breaks up
11	T: B does?
12	S1: That's what it's saying
13	T: B is saying you're forming Na_2O and HCl. You're forming … H's are connected to Cl's and O's are connected to the Na's. Did the O's and H's [*points to the water molecular model*] ever break apart?
14	Group: No
15	T: Oh! Okay. So maybe B isn't supported by that. Think about that one a little bit more
16	S4: C then? She was talking about the charges
17	S3: That's what I was going to say. It doesn't change its composition when you mixed it.

Figure 3.11. Part of Group 1D's dialogue with respect to the dissolution of NaCl in water

As Figure 3.11 illustrates, the course instructor guides students away from the incorrect response (the instructor initiates dialogue with the group in which they reason through why option B is incorrect). In more than one occasion, the course instructor stepped in to reason with the groups and initiated discourse that took its own life. These instances were coded based on what the course instructor was doing. The guiding questions for the codes were: 1) is the course instructor making links for the students between different representational modes (i.e., particulate, macroscopic, and the symbolic)? 2) is the course instructor prompting students to develop their own criteria? For instance, in the dialogue shown in Figure 3.11, the instructor states "So, may be B isn't supported by that. Think about that one a little bit more," A move that indirectly prompts the students to discuss the issue further and eventually change their response after developing different criteria. This dialogue fits the second criteria: course instructor prompts students to develop their own criteria. After tagging each recorded conversation in which the course instructor was involved in the discourse, I examined what the instructor's moves were (making links between multiple representations, prompting criteria development) and what that meant for the groups' chemical meaning making process. The findings of this analysis are shown in chapter 5.

3.7. Quantitative data analysis

To answer the third research question, *how do cooperative inquiry-based pedagogies – namely POGIL pedagogy – impact student understanding of the nature of ionic compounds in solution*, I analyzed (1) how the class as a whole and (2) the ten different groups in the study represented dissolving ionic solids before and after the POGIL activities (remember the goal of this study was to examine students' conceptions of ionic compound in solution, thus this analysis focused on only how students represented dissolved ionic compounds – that is, ionic solids in aqueous environment). Because particulate-level and symbolic-level data was available, the analysis was divided along those same lines. I will therefore provide further details of the symbolic-level and the particulate-level data analysis under separate headings.

3.7.1. Symbolic-level data analysis

Analysis in the symbolic-level data relied on students' responses to the multiple-choice pre-posttest questions described previously. While the main data came from the immediate pre-posttest items, this was complemented by findings from the early-pretest as well as other qualitative responses. For instance, for class-level analysis, the percent of students who got the correct response for each of the ionic solids present in the immediate pre-posttest questions were computed and the average class scores compared (i.e., only 15% correctly identified what happens to dissolving ionic solids in the pretest vs. 80% in the posttest). Students' written responses in the early pretest data (i.e., what happens to dissolved KI) as well as the groups' transcribed conversations were used to complement the findings in the symbolic-level data (e.g., few students mentioned dissolved KI dissociates into ions in the early pretest which is consistent with the low percentage choosing the correct response in the multiple-choice questions).

The symbolic-level data was similarly used to measure student retention of materials learned during the POGIL activities. You may recall that the midterm exam, administered about two weeks after the POGIL activities, asked student to choose the correct multiple-choice option for equations representing the dissolution of $MgBr_2$. The students' ability to correctly answer this question served as a mechanism to examine whether or not students retained what they learned about the dissolution process of ionic compounds during the POGIL activities.

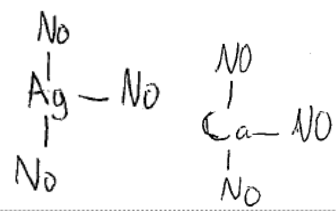
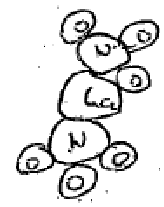
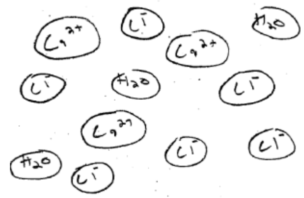
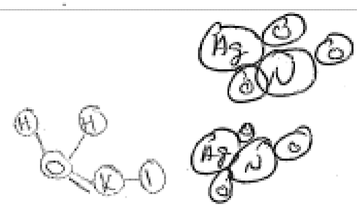
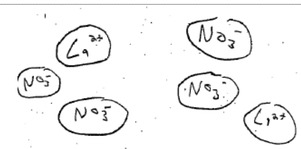
3.7.2. Particulate-level data analysis

The early pretest items administered during the first week of classes asked students to generate particulate diagrams representing what happens to KI dissolved in water and similarly to balance and draw the atoms, molecules, and ions when aqueous solutions of $AgNO_3$ and $CaCl_2$ are mixed to form solid AgCl and aqueous $Ca(NO_3)_2$. The posttest items asked for particulate drawings of $Ca(NO_3)_2$ and $CaCl_2$. Student drawings of these items were coded into one of three major codes: i) molecular framework with discrete atoms, ii) ionic framework with discrete ionic species, and iii) an all-encompassing other category. Examples and further descriptions of these categories are shown below.

The categories were based on previous literature findings that suggest students often use a covalent bonding model to represent ionic compounds at the particulate level (Nyachwaya, Mohamed, Roehrigm Wood, Kern & Schneider, 2011; Taber, 1998). Thus, based on this earlier work, representations in which ionic compounds were appropriately represented were coded as using "ionic framework." Those in which the ionic compounds were shown as covalently attached to each other were coded as using "molecular framework." Drawings that did not fit either of these two categories for dissolved ionic solids were coded as "other." The following illustrate each of these categories further.

Table 3.7 shows an example of each of the categories. Drawings using a molecular framework depicted dissolved ionic compounds as molecular species that appear to be connected through covalent bonds (see Table 3.7). Drawings using an ionic framework show dissolved ionic compounds as discrete ions separated in space and randomly distributed. Some students show the water molecules hydrating the ionic species while others omitted the water molecules (see Table 3.7). Drawings in the other category included dissolved ionic compounds amalgamated into water molecules as one large molecule or individual atoms in discrete molecular and ionic compounds grouped into inappropriate molecules (see Table 3.7). Most of these categories and descriptions were based on our earlier work with students' particulate representations of molecular and ionic compounds (Nyachwaya, Mohamed, Roehrig, Kern & Schneider, 2011). Analyses in chapter 6 provide fuller description and more examples of each of these categories.

Table 3.7
Sample student particulate drawings illustrating major categories

Category	Sample from pre-POGIL test	Sample from post-POGIL test
Molecular framework Sample pre-post drawings of AgNO3 and $Ca(NO_3)_2$		
Ionic framework Sample pre-post drawings of $CaCl_2$		
All-encompassing "Other" Sample pre-post drawings of KI, $AgNO_3$ and $Ca(NO_3)_2$		

Once student drawings were coded into one of three themes based on what framework the students used to represent the dissolved ionic compounds at the particulate level, the frequencies in which each theme occurred was tabulated. For instance, 71.2% of 177 pre-POGIL drawings depicted dissolved ionic compounds as molecular entities in which discrete ionic species were shown as though covalently bonded through electron sharing (see Table 3.6 above). These drawings were coded as using molecular framework. Full analysis of the particulate-level data will be shown in chapter 6.

3.8. The role of the researcher

In addition to data collection and analysis, I was involved in co-designing and creating the POGIL activities used in this study. I have similarly, prior to data collection, advised the course instructor on how to run the POGIL activities effectively and how to create effective cooperative learning groups. During the data collection phase, I was present in the meetings but limited my participation to classroom observation and note taking. Because the course instructor has informed students that I authored the POGIL activities they were using, there were some unavoidable instances in which students sought my help. However these instances were limited to helping students understand how the magnetic 3D molecular models worked or what a particular question in the activity was asking. When that happened, these conversations were recorded and identified in the sociochemical dialogue. It is my belief that these rare occurrences did not bias the data or color it one way or the other.

3.9. Advantages, disadvantages, and validation of the research design

Validity for the qualitative studies differs from the quantitative pre–posttests. The greatest threat to the qualitative studies may come from three sources (Maxwell, 1996)—data interpretation, description, and the theories formed in response to the data. However, the study was designed carefully to assure high confidence in data validity through the use of multiple data sources, what Creswell (2003) referred to as thick description. The POGIL activity worksheets, recorded audio conversations, and the collected artifacts provided rich streams of data containing large quantities of participant cognitive activities and conversations. Evidence of the claims and conclusions made as a result of the study comes from the preponderance of examples provided by the multiple data.

Another way that a threat to validity of the qualitative studies is addressed is to go back to audio-recorded conversations and examine the accuracy and precision of the transcripts with respect to having captured student's conceptualization. The transcription was done by trained undergraduate students at the University of Minnesota STEM Education Center. Once I received these transcripts, I doubled checked for accuracy and precision. This “double check” addressed the threat that researcher voices were inserted on the data. Other ways threats were minimized to data interpretation included the invitation of chemical educators to analyze the data and to solve any discrepancies in interpreting the data through dialogue and discussions.

The threat to the quantitative data comes from the lack of traditional control group in the chosen research design—one-group treatment approach. This suggests that while the quantitative data in this study may inform discussions of cause and effect about students’ representational fluency, it will not, unlike truly controlled experiments, provide definitive cause-effect relationship. However, the concurrent triangulation approach chosen for this study controls for this validity threat to the quantitative data. Integration of the qualitative data with the quantitative data ensures the validity of the results obtained from the quasi-experimental approach. Another point worth making here is that the aim of the present study is not to investigate the effectiveness of POGIL approach over traditional or nontraditional methods of instruction but rather whether POGIL improves students’ representations of ionic compounds. Thus, a traditional control group was not necessitated by the research questions and aims of this study.

A key characteristic of the experimental approach used here is important to highlight, as it provides both advantages and drawbacks to the approach. During the POGIL activities, students discussed the problems aloud and their vocalization of the tasks is audio-recorded for analysis of how group thinking influences students’ representations of ionic compounds. This is advantageous in that it shows the normative ways in which groups reason through a problem and provides hints about how group thinking influences individual students' behavior. The drawback is that cognitive thinking might be an individual phenomenon and therefore group thinking might not be reflective of what individual students think about the representational forms. Each student's own thinking is captured in the individual measures of assessment (e.g. pre–posttests, midterm exams). As discussed below, reliance on individual drawings in the absence of individual interviews has also both advantages and drawbacks.

The analytical framework used for the qualitative study was episode analysis. As is common in episode analyses, there are some advantages and drawbacks to this approach. The drawback is that it sacrifices some of the depth and richness in individual responses that is often associated with qualitative traditions in order to capture the breadth of variations in students' representations of ionic compounds at the particulate level. In other words, student responses provide a very broad look at the variation among students' ways of representing ionic compounds. But this drawback is advantageous as well; as it achieves a breadth that would be impossible, practically speaking, with more in-depth qualitative approaches, for instance, in-depth individual interviews. However, it should be noted drawings without further explanation only provide surface information and one cannot do more than infer the ideas/conceptions that underlie the student's drawings. An experienced chemistry educator will likely be able to speculate about what ideas/conceptions the students' drawings reveal but such data will not include any information that could be used to confirm or disconfirm such inferences.

CHAPTER 4

Identification of Sociochemical Norms

"We're going to draw [matrix of NaCl] in nice big chunks. So there's four Cl's, right? Is Cl the bigger one? I think it's smaller." (Student A)

"Wouldn't it be bigger? It has bigger protons in it. There is four in each, right?" (Student B)

Dialogue between two students in this study

Chapter two described how over the last three decades the chemistry education community widely embraced cooperative and inquiry-based pedagogies as part of their instructional tools. There I described in some detail the documented benefits of these instructional strategies and their ability to provide opportunities for classroom discourse in which students collaboratively develop understandings of core chemical ideas (Becker, Rasmussen, Sweeney, Wawro, Towns & Cole 2012; Osborne, 2010; Paulson, 1999). For instance, I described how the key components of POGIL pedagogy are the "active engagement of all students through group learning, guided inquiry materials based on the learning cycle paradigm" (Moog, Creegan, Hanson, Spencer, and Straumanis, 2006, p.42). I noted how such structure elicits group construction of concept understanding and knowledge growth. This chapter and the next one examine how the social aspects of cooperative activities and group thinking influence individual student learning outcomes in chemistry. This chapter particularly addresses the first central question of the study:

***Research Question 1*: How does group thinking during a cooperative inquiry-based activity on chemical bonding shape and influence college students' conceptions of ionic compounds in solution?**

To answer this central question, it was important to first examine the process by which sociochemical norms were established in groups and how these norms influenced students' conceptions of ionic compounds in solution. In describing the development of these normative ideas, I found it useful to first examine patterns within individual groups before across looking at group patterns. It also became clear, once data collection ensued, the course instructor made several important practical moves that aided the groups' discourse practices. However, this chapter mainly examines student-initiated discourse and sociochemical norms while chapter 5 examines teacher's practical moves and its influence on group discourse and student learning.

There are three main sections in the chapter – 4.1, 4.2, and 4.3. Section 4.1 examines the development of sociochemical norms that pertain to group-generated criteria for *what counts as acceptable chemical justification* for balanced symbolic chemical equations representing dissolving ionic solids in water. Section 4.2 follows a similar structure but examines unfolding sociochemical dialogues related to the electrical conductivity of chemical compounds. The final section of the chapter, section 4.3, examines how the sociochemical dialogues described in sections 4.1 and 4.2 influence student thinking. The guiding criteria for data analysis were the analytical codes and criteria described in chapter 3. As a reminder, these were:

- Code GNC (Group Negotiated Criteria). This code was used when there were indications of the student groups negotiating and developing criteria for what counts as an acceptable justification for a chemical phenomenon (e.g., the dissolution of ionic compounds).
- Code AGC (Across Group-Negotiated Criteria). This code was used when one or both of the following criteria were satisfied:
    a. Different autonomous groups developed and used similar criteria to explain the same chemical phenomenon.
    b. Different groups used the same criterion as justification for different topics.
- Code SST (Shifts in Student Thinking). This code indicated there was a shift in individual student thinking brought about by opposing viewpoints or new information contradicting initial position(s) the students held.

As described in chapter three, episodes make up the unit of data analysis. To re-orient the reader, recall episodes are organized in a column format such that group dialogue is shown first followed by statement identification (codes) and short comments and/or interpretations. Lines in the dialogue are numbered sequentially for easy reference (the code LN in the paragraphs refers to the lines in the dialogue).

4.1. The Development of Sociochemical Norms: Criteria for Ionic Compounds

The results of the analysis of group episodes make it apparent that specific ways of thinking unique to the study of chemistry became normative in the groups studied. That is, groups routinely developed and used chemistry-driven criteria to explain the physical and chemical properties of dissolving ionic solids. The following section describes the development of these normative ideas and how they were used by the groups.

4.1.1. Patterns within groups: Group Negotiated Criteria (GNC)

4.1.1.1. Context

Before I describe the findings, first recall the context in which the episodes occurred. As described in chapter 3, the context was the following: after observing an instructor-led macroscopic demonstration of NaCl dissolved in water, the students used magnetic molecular kit to model the dissolution process, and drew particulate diagrams showing what happened before and after the mixing of NaCl in water. In the group conversations explored in this chapter, students were attempting to justify their response for which balanced chemical equation was in agreement with their particulate drawing (see chapter 3 for full activity description). Findings are presented as individual cases of group dialog in chronological order, starting with the dialogue from groups meeting in the first session (1A – 1D) followed by groups meeting in the 2nd session (2A – 2B) and concluding with those meeting for 3rd session (3A and 3B).

4.1.1.2. Group 1A's sociochemical dialogue

Group 1A was homogenous in terms of gender mix, consisting of four females each playing different cooperative role they self-selected. Student 1 (*S1*) was the group's facilitator, *S2* the spokesperson, *S3* the quality control/recorder, and *S4* a process analyst. The group appeared to be animated and had good rapport. Once they took up their different roles they immediately started discussing the problems in the activity. Figure 4.1 shows the episode in which the group discussed the dissolution process of NaCl in water.

Directions: Based on your particulate diagrams, which of the following balanced equations shows what happens to sodium chloride (NaCl) placed in water?

a. NaCl *(s)* → Na *(aq)* + Cl *(aq)*
b. 2NaCl *(s)* + H_2O *(l)* → 2HCl *(aq)* + Na_2O*(aq)*
c. NaCl *(s)* → Na^+*(aq)* + Cl^-*(aq)*
d. NaCl *(s)* → Na^+*(s)* + Cl_2^-*(s)*
e. NaCl *(s)* → Na^+*(s)* + Cl^-*(s)*

	Dialogue	Code	Comments/Interpretations
1	S1: So the water didn't change [*points to the molecular model of water in their tray]*, so the water goes with … so it's not A. Are they [*pointing to Na and Cl in their drawing]* aqueous?	GNC AGC*	*Initiating move; S1 proposes justification (water didn't change) and asks for clarification (are they aqueous)*
2	S2: Yeah, they're aqueous	GNC/ AGC	*Confirmatory response statement*
3	S3: So, wouldn't it be C? Those are the only aqueous	GNC/ AGC	*Consensus checking statement- justifies why Acknowledgement statement*
4	S4: Yeah. That's what I'd think	GNC	
5	S2: They're still ions	GNC AGC	*S2 proposes a new criteria (needs to be ions)*
6	S1: So a plus and negative would be good. And it's balanced. Good. So now activity three. [*end of episode*]	GNC/ AGC/ SST	*This is coded both GNC and SST as S1 did not initially propose +/- , student shifts thinking in LN 6*

Figure 4.1. Group 1A's dialogue on choosing correct equation for NaCl dissolved in water. *The code AGC is used when a particular idea, e.g., ions/aqueous, was used by different groups in the study –that other groups used similar criteria.

In the initiating move of this episode (LN 1), *S1* proposed that water did not change and, looking at the 3D molecular models of Na^+ and Cl^-, posed to the group a clarification question ("are they aqueous?" LN 1). In response to *S1*'s question, *S2* provided a confirmatory response of "Yeah, they're aqueous" (LN 2). There was no follow-up on *S1*'s idea that *water did not change* and this criterion was dropped from the further ensuing group discussion. We see in line 3 that *S3* proposed option C of the multiple-choice question as the most likely valid option but sought group consensus as indicated by her statement of "So, wouldn't it be C? Those are the only aqueous" (LN 3).

In proposing option C as the most likely answer, *S3* used the previously discussed idea of "aqueous" as justification for why she thought C is the correct response. Responding to *S3,* another member of the group, *S4,* acknowledged that C is likely the correct response ("Yeah. That's what I'd think" LN 4).

In addition to the criterion of dissolving salts being aqueous, the idea of ions as criterion for selecting the correct response is proposed by *S2* when she states "They're still ions" (LN 5). Following this back and forth dialogue the group used the chemical ideas of "aqueous" and "ions" as a justification for why they selected option C of the multiple-choice question. This is summarized by *S1,* the group's facilitator, in line 6 of Figure 4.1 as "So a plus and negative would be good. And it's balanced."

A key claim in this research is that groups negotiate criteria for what counts as a chemical justification for their explanations. Group 1A's dialogue is characterized by several statement types that support this idea of socially negotiated chemical meaning making. These include clarification statements posed to the group (*S1*, LN 1), confirmatory response statements (*S2*, LN 2), consensus checking statements (*S3*, LN 3), and acknowledgement statements (*S4*, LN 4). The nature of these discursive practices suggests the group is involved in the collective development of chemical justifications to explain the dissolution of NaCl in water.

The chemical ideas of 'aqueous' and 'ions' as a critical criteria for selecting the correct equation to represent the dissolution of ionic solids in water was not discussed by the course instructor *in priori.* Rather this was student-negotiated criteria during the activity. The fact that the group repeatedly used this criteria (i.e., ionic solids separating into ions and becoming aqueous) in their discourse to justify their reason for selecting a particular chemical equation to represent the dissolution process suggests these ideas became normative within the group.

4.1.1.3. Group 1B's sociochemical dialogue

Group 1B, consisted of 3 females. *S1* was the group's facilitator, *S2* the spokesperson, and *S3* the quality control/recorder. Figure 4.2 shows the group's sociochemical dialogue.

	Dialogue	Code	Comments/Interpretations
7	S2: We don't ever say the water, right? That was the issue yesterday in lecture. B isn't right. And these [*points to Na and Cl*] are all in ions. Or are they– ?	GNC/ AGC	*Dialogue initiating and information request question posed to the group*
8	S1: They are all ions	GNC/ AGC	*Confirmatory statement – responses to S2*
9	S2: So, it can't be A	GNC	*Follow-up statement based on claims made in lines 7 & 8*
10	S3: How do you know they're all ions?	SST	
11	S1: That's why they have the charge. The plus and the minus. What makes an ion?	GNC/ SST	*Explanatory statement*
12	S3: It's charge …?	SST	*Explanatory statement (S1 explains to S3 how one knows why Na and Cl are ions*
13	S1: Yeah, and what makes them charged? They gain or lose an electron making them ions! Because you don't really find just this very often	GNC/ SST	*SST because there is request of information and skeptical and challenging questions*
14	S2: I'm pretty sure it's C. That's my guess. They are not solids, right?	GNC/ AGC	*Group consensus checking statement*
15	S1: And it'd have to be aqueous because of the water	GNC/ AGC	*Acknowledgement and confirmatory statement*
16	S3: Yeah [*group circle C in their answer sheet*]	GNC/ SST	*SST because S3's earlier skeptical questioning appears to shift to acceptance*

Figure 4.2. Group 1B's dialogue on choosing correct equation for NaCl dissolved in water.

There are several points in Group 1B's dialogue that show how the group is involved collectively in developing criteria to describe dissolving ionic solids and how such criteria is critical for selecting the correct equation to represent the dissolution process symbolically. In the initiating move of this episode, *S2* states that Na^{+} and C^{l-} "are all in ions" (LN 7) but then seems to doubt herself, asking the group for clarification: "Or are they?" (LN 7). Before *S2* could finish her thought she is interrupted by *S1* who confirms that "They are all ions" (LN 8). This practice of finishing each other's thoughts is an indication of collective group effort and meaning making. *S3* asks "How do you know they are ions?" (LN 10). In lines 11 and 13, *S1* explains to *S3* that they have charges as a result of gaining or losing an electron, making them ions (LN 13, Figure 4.2). The exchange between *S1* and *S3* illustrates how, in cooperative learning setting, the process of discussing a concept with peers allows for instant feedback that can lead to shifts in student thinking and understanding (Smith, 1987; Hollabaugh, 1995).

The group settled on the idea that dissolving ionic solids need to include ions and used this as exclusionary criterion to rule out option A of the multiple-choice question – "So, it can't be A" (*S2,* LN 9). The idea of ionic solids becoming aqueous when dissolved comes up as criterion at the end of the episode. In line 14 of Figure 4.2, *S2* asks "They are not solids, right?" *S1*, on the other hand, states "And it'd have to be aqueous because of the water" (LN 15). *S3* acknowledges this discussion by simply stating "Yeah" (LN 16). Thus, the students seem to have used both the ideas of "ions" and "aqueous" as guide to select the correct multiple-choice option (the group selected C as their final answer).

This group's dialogue is characterized by several statement types that support the idea of socially negotiated chemical meaning making. These include clarification statements posed to the group (Lines 7, 10, and 13), confirmatory response statements (lines 8 and 15), consensus checking statements (Lines 14 and 15), and acknowledgement statements (e.g., LN 16). Again, the nature of these discursive practices suggests the group is involved in the collective development of a chemical justification for the dissolution of NaCl. Moreover the group collectively developed the ideas of 'aqueous' and ions' as a guide for selecting the correct response. Thus the students were thinking about providing chemical justification as a whole and used the ideas they developed as guide for selecting their responses.

4.1.1.4. Group 1C's sociochemical dialogue

Group 1C was heterogeneous in terms of gender, with two females (*S1* and *S2*) and one male (*S3*). *S1* was the group's facilitator, *S2* the spokesperson, and *S3* quality control/recorder. Figure 4.3 shows the group's dialogue.

	Dialogue	Code	Comments/Interpretations
17	S1: This should be B because … (mumbled) … the fact that it's showing two ions [*points to 2NaCl*]. Plus the H_2O …	GNC/ AGC	*Initiating move; S1 focuses on water reacting with NaCl*
18	S2: What are you guys looking at	GNC	*Procedural talk; no bearing on problem solution*
19	S1: We are on 3	GNC	*Procedural talk*
20	S2: Yeah, B makes sense	GNC/ AGC	*Confirmatory response statement; S2 → S1*
21	S1: For one thing it's the only one you're adding water to. The other ones aren't adding water to it. They are have an equation without water	GNC/ AGC	*Provides chemical justification why option be would be correct*
22	S3: It's definitely not D and E. I don't think it's A or C because they don't have the water in the equation	GNC/ AGC	*Confirmatory Consensus-checking statement*
23	Okay [*group chooses B and moves on to the next activity]*		*Acknowledgement statement*

Figure 4.3. Group 1C's dialogue on choosing correct equation for NaCl dissolved in water.

In the initiating move of the episode, *S1* states that the answer should be option B because "it's showing two ions [*points to 2NaCl*]; *emphasis is mine*. Plus the H_2O" (LN 17). *S2* confirms this suggestion by simply stating "Yeah, B makes sense" (LN 20). In line 21, *S1* states more strongly why she believes option B is correct by stating "For one thing it's the only one you are adding water to. The other ones aren't adding water to it. They have an equation without water" (LN 21). Here, *S1* focuses on the lack of water in the equations in options A and C-E. *S3* similarly rules out option A and C because "they don't have the water in the equation" (LN 22). Although *S3* rules out D and E as option ("It's definitely not D and E" LN 22), he does not state the reason for excluding them as viable options. In this sense, the group uses the presence of water as exclusionary criteria for selecting the correct response.

This group focused on symbolic features present in the balanced equation (the presence or absence of water molecules) as a guide for their selection and response. Thus, even though the group chooses initially the wrong answer, nevertheless they seem to use chemical justification (the presence or absence of a particular molecule) for selecting their answer. Moreover, this group's dialogue is characterized by several statement types that support the idea of socially negotiated chemical meaning making. These include clarification statements posed to the group (LN 1, 21), confirmatory statements (LN 20, 22), and acknowledgement statements (LN 23).

4.1.1.5. Group 1D's sociochemical dialogue

Group 1D had heterogeneous gender mix with two females (*S1* and *S3*) and two males (*S2 and S4*). *S1* was the group's facilitator, *S2* the spokesperson, *S3* the quality control/recorder, and *S4* the process analyst. The group as a whole functioned well with members finishing each other's thoughts and seeking input from other members. Figure 4.4 shows the group's sociochemical dialogue.

	Dialogue	Code	Comments/Interpretations
24	S1: What equation do you think it is?	GNC/ SST	*Information seeking statement*
25	S2: The only one that makes sense is B because it's the only one that is adding water	GNC/ AGC	*Response statement. This could also be confirmatory statement*
26	S1: When you add salt to water you get … the dispersal of that	GNC/ AGC	*Challenge statement (S1 is challenging S2's assertion)*
27	S3: Or is it saying that –	GNC	*Clarification question/Information request*
28	S4: It's not D or E because those are both solids. It can't be those two. B is the only one that makes sense because it's the only one adding the water	GNC/ AGC	*Follow-up statement. S4 uses chemical justification as to why B is the correct option*
29	S3: But it has HCl and the Na is with the O. This [points to Na] won't connect to the negative since it's extra …	GNC/ AGC	*This statement challenges the claim made by S4*
30	S1: It really [*points to the molecular model of water*] doesn't break apart	GNC/ AGC/ SST	*Supporting statement – provides support for the claim made by S3 in line 29*
31	S2: It just bonds [*Group appears to settle on B although S1 and S3 are not convinced … course instructor interfered and group chose C*]	GNC/ AGC/ SST	*Response statement – S2 is responding to S1's statement in line 30*

Figure 4.4. Group 1D's dialogue on choosing correct equation for NaCl dissolved in water.

Group 1D's discourse was prototype example of sociochemical dialogue in which members of a group hold contrary views and must dialogue to come to an agreement. Johnson and Johnson (1987) describe this, in the context of cooperative learning groups, as controversy decision-making process. The authors explain that "controversy exists when one student's ideas, information, conclusions, theories, and opinions are incompatible with those of another, and the two seek to reach an agreement" (p.224).

In the ensuing discourse in Figure 4.4, *S2* is adamant answer B is the only option that makes sense because it shows the only equation adding water (LN 25). *S1* provides the counter-argument that "when you add salt to water you get the dispersal of that" (LN 26). This suggests *S1* knows salts dissociate into ions when dissolved in water. *S3*, who appears to be in agreement with *S1*, attempts to make statement when she is interrupted by *S4* who states “It’s not D or E because those are both solids. It can’t be those two. B is the only one that makes sense because it’s the only one adding the water” (LN 28). Thus the students interrupt each other and seem to have a lively discourse about which multiple-choice options to select.

Both *S2* and *S4* base their arguments of why option B is correct on the fact that this option has the only equation showing water. *S3* presents a different argument of why B is incorrect: “But it has HCl and the Na is with the O” (LN 29). Here, *S3* is pointing out to others how option B is showing formation of HCl and Na_2O, chemicals the group did not observe when modeling the dissolution process via the molecular kit. *S1* appears to pick on this cue and uses the 3D molecular model. Similar to *S3*, she attempts to use the model to point out that water remained intact in the model (“It really doesn’t break apart” LN 30), something that should have happened if HCl and Na_2O were to form. However, she is interrupted by *S2* who erroneously completes *S1*’s thought by stating “It just bonds” (LN 31). Here, it appears *S2* wants an equation that shows the water bonding with the salt and option B seems to meet his criteria of the water bonding with the salt. Thus, despite the contrary evidence proposed by *S1* and *S3*, *S2* did not change his thinking at this point of the episode and the group leaned towards option B as their response even though *S1* and *S3* seemed opposed to this view.

There were a lot going on in this group’s dialogue. Two of the students (*S2* and *S4*) focused on water as chemical justification for why option B is the correct response. For these two students, the criteria to determine the correct equation for dissolving ionic solids is whether or not the symbolic equation shows the presence of water and whether or not water is reacting with the salt. To *S1* and *S3* the main criterion appears to be an equation showing the "dispersal" of salts into ions (see *S1*, LN 26; *S3*, LN 29). Both seem to also focus on the observation that water did not break up (*S1*, LN 30) and that there was no chemical transformation occurring (*S3*, LN 29). Although members of the group hold contrary viewpoints, nevertheless they are involved in a back-and-forth dialogue in which they are attempting to develop a common response. In this sense, the students are involved in group construction of meaning making. They are not, for instance, deciding individually what the correct response is but are engaged in collective discourse about what equation to select.

Group 1D appears to be involved in developing criteria for what counts as acceptable chemical justification for the dissolution of ionic salts in water. This group's dialogue is also characterized by statements indicating group effort. These include request and information seeking statements (LN 24, 7), position challenging statements (LN 26, 29), follow-up statements (LN 28) and support statements (LN 30). The group also appears to negotiate what equation to select by using chemical justifications (presence of water in the symbolic equation, chemical change, and presence of ionic species) as a guide for their response. Thus Group 1D is involved in meaning making process, collective thinking, and development of chemical-based reasoning.

4.1.1.6. Group 2A's sociochemical dialogue

Group 2A was homogenous with respect to gender, with three female students (*S1, S2, and S3). S1* was the group's facilitator, *S2* the spokesperson, and *S3* the quality control/recorder. It was not apparent from their conversations how they decided the roles, but, as in the other groups, the roles were self-selected and not assigned by the course instructor. Figure 4.5 shows the group's dialogue with respect to which multiple-choice option to select.

	Dialogue	Code	Comments/Interpretations
32	S3: It'd be "C" I believe because it's not a chemical	GNC/ AGC	*Initiating move; S3 proposes plausible answer and reason*
33	S2: It's not actually reacting with the water. It's just breaking up into different ions	GNC/ AGC	*Qualifying response; S2 uses the 3D kit to mix NaCl & water and makes observation*
34	S1: That makes sense	GNC	*In lines 3-6, students*
35	S3: It can't be A because….	GNC	• *finish each other's thoughts*
36	S2: It has to be ions	GNC/ AGC	• *rule out other options since they do not meet their conception of what should have happened*
37	S3: It needs to be ions so it's not A. There's no chemical change so it's not B. It's aqueous, yeah. So that makes sense	GNC/ AGC	
38	S2: Totally did that wrong on the pre-assessment	SST	*We interpret this as indication of shift in student thinking*
39	S3: I knew that in the back of my mind, but when I first think about it… yeah	SST	*Indication of shift in student thinking*
40	S2: I think whatever you have is okay [*student addresses group recorder*]		*procedural statement; no bearing on group consensus*
41	S1: We said C because A doesn't have ions and B we didn't change anything chemically. D and E just aren't aqueous	GNC/ AGC	*Summary/consensus checking statement; part of group discussion dynamics*
42	S3: That makes sense	GNC	*Acknowledgement statement.*

Figure 4.5. Group 2A's dialogue on choosing correct equation for NaCl dissolved in water.

As can be seen in Figure 4.5, the students appear to negotiate a criterion for what counts as an acceptable balanced equation to represent the dissolution of ionic compounds in water (LN 32 – 42). Initially, *S3* proposed the correct response must be option C because this answer does not represent a chemical change (LN 32). *S2* immediately refines this justification by restating it in the context of the manipulatives the students used in the activity, stating “It’s not actually reacting with the water” (LN 33) and adding a justification from observation, “It’s just breaking up into different ions” (LN 33). Through further refinements and back-and-forth dialogue, we see the group collectively develop a shared criterion for what counts as justifiable balanced equation, summarized by *S1* as: needs to break up into different ions, does not change chemically, and needs to be aqueous (LN 41).

The unfolding sociochemical dialogue of this group is characterized by statement types indicative of collective effort, including confirmatory statements (LN 27), consensus-checking statements (LN 27-29), summary/clarification statements (LN 33) and acknowledgement/support statements (LN 34), showing that the group is actively involved in meaning making. These statements indicate group constitution of meaning (code GNC in the episode) in the sense that they cannot stand on their own but rather take on meaning and function only in the context of the group exchange (Wells, 1993, 1996).

Note that in the discourse shown in Figure 4.5 the group repeatedly used the ideas of ionic solids separating into ions and becoming aqueous as justification for their response. There was also appeal to the idea of the compound not undergoing chemical transformation when dissolved. Thus these chemical ideas (ions, aqueous, chemical change) became normative throughout the duration of the group’s discourse.

4.1.1.7. Group 2B’s sociochemical dialogue

Group 2B was homogenous group of three males (*S1, S2,* and *S3*). *S1* was the group’s facilitator, *S2* the spokesperson, and *S3* the quality control/recorder. Figure 4.6 shows the group’s sociochemical dialogue.

	Dialogue	Code	Comments/Interpretations
43	S2: What do you think? D? [*circles D*]	GNC	*Information seeking move*
44	R: Why did you choose D?		
45	S2: I don't know. We were just looking at it. We didn't really answer it yet [*R walks away*]	GNC	*Procedural talk*
46	S1: B says the water broke apart. These things [*points to water model*] when in really … weren't they just really like that [*again points to the water model*]? Well, the sodium and chloride should be ions. I just didn't put B. I didn't guess yet [*pauses*]. Yeah, it's C.	GNC/ AGC	*S1 focuses on water and also points out that NaCl will dissociate into ions. His statements can be classified as confirmation and consensus checking statements*
47	S3: C?	GNC/ SST	*Consensus checking statement*
48	S1: That's what I put	GNC	*Follow-up response*
49	S2: Yeah, it has to be aqueous and it has to move from solid to aqueous	GNC/ AGC	*Acknowledgement and support statement*
50	S1: Yeah, that is why I put C [*episode ends here*]	GNC	*Acknowledgement statement*

Figure 4.6. Group 2B's dialogue on choosing correct equation for NaCl dissolved in water.

The group's dialogue with respect to the dissolution of sodium chloride in water was rather short. All three did participate in the conversation although *S3* provided limited contribution in this particular episode. In line 46, *S1* provides justification for why option B is incorrect; arguing that option B suggests the water molecule broke apart when the group observed the water molecules remaining intact in their molecular model kit. S1 continues his thought and states "the sodium and chloride should be ions" (LN 46), developing the group's first criterion. *S2* provides a second criterion when he states "Yeah, it has to be aqueous and it has to move from solid to aqueous" (LN 49). *S1*'s follow-up acknowledgement statement "that is why I put C" (LN 50) suggests the group used both criteria ("should be ions" & "it has to be aqueous") to select option C of the multiple-choice question. *S3*'s contribution is limited to one consensus-checking statement in line 47. It is not apparent if he disagreed or agreed with other members of the group.

4.1.1.8. Group 2C's sociochemical dialogue

Group 2C had two females (*S1* and *S2*) and one male (*S3*). *S1* was the group's facilitator, *S2* the spokesperson, and *S3* the quality control/recorder. Figure 4.7 shows the group's sociochemical dialogue.

	Dialogue	Code	Comments/Interpretations
51	S1: We drew it, so we are good on that. So which of the following balanced equations shows what happens to NaCl placed in water?	GNC	*Initiating move; S1 reads activity question verbatim*
52	S2: B	GNC	*Follow-up response*
53	S1: I agree	GNC	*Acknowledgement statement*
54	S2: B?	GNC	*Consensus-checking statement*
55	S3: Yeah. For 3	GNC	*Response statement*
56	S2: No, 5.	GNC	*Follow-up response*
57	S3: Oh! I didn't get there yet [*episode ends*]		*Procedural talk*

Figure 4.7. Group 2C's dialogue on choosing correct equation for NaCl dissolved in water.

In the initiating move of the episode (LN 51), *S1* read verbatim what the question asked in the activity ("so which of the following balanced equations shows what happens to NaCl placed in water?" LN 51). *S2* responded by saying "B" (LN 52) in a follow-up statement. In line 53, *S1* acknowledged the selection of option B by simply stating "I agree" (LN 53). When *S2,* in consensus checking statement, asked "B?" (LN 54), *S3* responded by saying "Yeah. For 3" (LN 55). *S2* responded back by saying "No, 5" (LN 56). From the exchange between *S2* and *S3* in Figure 4.7, it appears the students were working on different problems of the activity (problem 3, which dealt with NaCl and problem 5, which dealt with methanol, CH_3OH) although they were using the magnetic molecular kit to mix sodium chloride in water. As members simply stated which multiple-choice option they believed was correct without backing or justification, it is difficult to determine which problem the students were working on.

From the above observations, the group does not appear to have implemented their cooperative roles, specifically the roles of quality control/recorder and process analyst. If the group took these roles seriously, the quality control/recorder would have made sure all members were working on the same problem. In this sense, Group 2C is a prototype example of dysfunctional group.

While this group's dialogue is characterized by statement types indicative of group thinking (e.g., consensus checking statement, follow-up and response statements, acknowledgement statements, and clarification statements), the group did not develop any criteria to guide their selection and response, regardless of what question they were discussing. Their whole dialogue on the dissolution process of NaCl in water was confined to discussing what letter to pick and what question they were working on. This group presents an example in which students did not negotiate for criteria on what counts as chemical justification for dissolving ionic solids.

4.1.1.9. Group 2D's sociochemical dialogue

Group 2D was homogenous in terms of gender make-up with four males (*S1–S4*). *S1* was the group's facilitator, *S2* the spokesperson, *S3* the quality control/recorder, and *S4* the process analyst. The group's dialogue showed animated discussion with members questioning each other's stance. Figure 4.8 shows the group's sociochemical dialogue.

	Dialogue	Code	Comments/Interpretations
58	S2: Well, it'd have to be mixed because it's mixed with water, but that doesn't make sense [*points to B as answer*]	GNC	*Initiating move; proposes an explanation but suggests option B doesn't make sense*
59	S3: I think it's C because the Na and Cl	GNC/ AGC	*Follow-up response statement*
60	S4: Is it B or D?	GNC/ SST	*Information request*
61	S3: It's not B	GNC	*Response statement*

62 S2: It can't be C because there is no H_2O	GNC/ AGC	*Rebuttal statement on why option C is not correct*
63 S3: Does there have to be?	GNC	*Skeptical questioning - challenges S2's claim*
64 S4: This one [*points to B*] has the 2 Na with the O because the O stays with it	GNC/ AGC/ SST	*Provides explanation of why he thinks B is correct*
65 S3: I think it's just trying to say what happens	GNC	*Explanatory statement*
66 S4: So you think it's C?	GNC/ SST	*Self-doubt after challenged -> SST*
67 S3: Because 2 NaCl makes hydrochloric acid and we don't have that. This one [*points to C*] shows the charge and makes more sense. If not B then I think that	GNC/ AGC/ SST	*Explanatory statement of why C is correct but self-doubts*
68 S3: So, you think it's C? [*Instructor interference*]	GNC/ SST	*Consensus checking statement*

Figure 4.8. Group 2D's dialogue on choosing correct equation for NaCl dissolved in water.

In the initiating move of the episode, *S2* argued NaCl must be mixed with water although the option B does not make sense to him (LN 58). It was not apparent from the dialogue why he thought option B did not make sense – only a hint that option B "does not make sense" (LN 58). *S3* at that point put forward option C as the correct option because it showed "Na and Cl" (LN 59). *S4*, another member of the group, asked if the correct response option should be "B or D" (LN 60). *S3* simply stated "it can't be B" (LN 61) but did not rule out option D. *S2*, on the other hand, refuted *S3's* suggestion of option C on the basis that "there is no H_2O" (LN 62). *S2* seemed conflicted: in the initiating move (LN 58), he argued option B did not make sense but also ruled out option C because "there is no H_2O" (LN 62).

From the unfolding sociochemical dialogue, it was apparent the students in Group 2D were thinking about chemical justification for their responses. In the initiating move, *S2* described the dissolution of ionic salts as "it'd have to be mixed because it's mixed with water" (LN 58). The correct chemical terminology would have been it 'became aqueous.' One can infer from this finding that *S2* probably did not have a good grasp of the nature of aqueous solutions, and hence the difficulty in describing the dissolving of salts in water. *S4*, on the other hand, interpreted the hydration of sodium ions in the model to mean a new bond forming between Na and Oxygen of H_2O ("This one [*points to B*] has the 2 Na with the O because the O stays with it" LN 64). Remember, the students had access to the magnetic molecular kit, thus when *S4* says "this one," he is using the kit and physically manipulating NaCl model surrounded by water molecules. This is what led him to think that option B, which shows the addition of water to NaCl, was probably the correct option.

This group appears to use extensive array of chemical arguments. For instance, when discussing why option B is incorrect, *S3* argued option B does not make sense "because NaCl makes hydrochloric acid and we don't have that," (LN 67) and moved on to suggest option was correct because it "shows the charge and makes more sense" (LN 67). Here, *S3* made a chemical argument against option B, (a chemical change would have resulted formation of HCl) and an argument for option C (it shows charges). Moreover, all students in the group were involved in the ensuing dialogue and attempted to convince each other based on chemical reasoning and justification. Thus¸ students were involved in developing what criteria counts as chemically justifiable for symbolically representing the dissolution of ionic salts in water.

4.1.1.10. Group 3A's sociochemical dialogue

Group 3A was homogenous group of three males (*S1, S2, and S3*). *S1* was the group's facilitator, *S2* the spokesperson, and *S3* the quality control/recorder. Figure 4.9 shows the group's sociochemical dialogue.

	Dialogue	Code	Comments/Interpretations
69	S1: Which of the following balanced equations shows what happens? It's going to be NaCl … goes to $Na^{+}Cl^{-}$, right?	GNC/ AGC	*Initiating move – proposes possible response*
70	S2: Would it be Cl_2^{-} since it's a diatomic molecule?	GNC	*Follow-up response; seeks group in put*
71	S3: It'll be aqueous, not a solid, so I think it's C	GNC/ AGC	*Established new criteria*
72	S2: Yeah	GNC	*Acknowledgement statement*
73	S1: It's mixed with water so that means it's aqueous [*group chose C and moved on* t]	GNC/ AGC	*Acknowledgement/support statement*

Figure 4.9. Group 3A's dialogue on choosing correct equation for NaCl dissolved in water.

This group's dialogue was rather short and to the point. In the initiating move, *S1* suggested "It's going to be NaCl … goes to $Na^{+}Cl^{-}$" (LN 69) and followed this with clarification/confirmatory request statement of "right?" (LN 69). This move established the criteria of ionic salts dissociating into ions in the groups mind. *S2* responded to *S1* by suggesting that the chloride ion should be Cl_2^{-} instead of Cl^{-} "since it's a diatomic molecule" (LN 70). No one seems to respond to *S2*'s suggestion of Cl^{-} being Cl_2^{-} and the group moves on. In the dialogue in lines 71 – 73, the group established the criterion of "aqueous" as necessary for equations showing dissolution of ionic solids. Thus the group established these two criteria "ions and aqueous" and used it to select option C of the multiple-choice questions. The group's dialogue was rather short but nevertheless characterized by statement types indicative of group effort including follow-up statements, information-seeking moves, and support/acknowledgement statements.

4.1.1.11. Group 3B's sociochemical dialogue

Group 3B was a homogenous group of three females (*S1, S2, and S3*). *S1* was the group's facilitator, *S2* the spokesperson, and *S3* the quality control/recorder. Figure 4.10 shows the group's sociochemical dialogue.

	Dialogue	Code	Comments/Interpretations
74	S1: Would it be C? No, we have to do the plus H_2O, so …	*GNC/ AGC*	*Seeks group in-put while making a claim*
75	S3: B? It's the only one that has plus H_2O. What happens to a molecular compound when you put them in water?	*GNC/ AGC*	*Support statement for S1's suggestion*
	[*group chose B and moved on to the next activity but came back to this problem after talking to another group*		
76	S2: [*Talking to another* group] B. Is that what you get?	*GNC*	*Seeks in-put*
77	S4: Water doesn't break apart though	*GNC/ AGC/ SST*	*Providing challenge to option B based on chemical reasoning*
78	S1: That is true, even though none of the other ones say H_2O	*GNC/ SST*	*Support statement*
79	S3: Why don't they show the water?	*GNC*	*Skeptical questioning*
80	S1: The water doesn't break apart. It's C then	*GNC/ AGC*	*Response move*
81	S3: But C doesn't show H_2O	*GNC/ AGC*	*Challenging statement*
82	S2: Did you get C then? [*Talking to another group; confirmed they had C as an answer*]	*GNC*	*Seeks input from other groups*
	[*episode on NaCl ends here and group moves on to new activity*]		

Figure 4.10. Group 3B's dialogue on choosing correct equation for NaCl dissolved in water.

Group 3B's dialogue makes apparent they were involved in the development of criteria that would allow them to select an option. In the initiating move of the episode, *S1* asked the group if the answer would be C but then suggested it could not be because "we have to do the plus H_2O" (LN 74). In line 75, *S3* completed *S1*'s thought, stating "B? It's the only one that has plus H_2O. What happens to a molecular compound when you put them in water?" It is evident from this discussion the group was focused on the presence or absence of water from the symbolic chemical equation. Based on this criterion, the group chose option B as their response before talking to other groups and subsequently changing their option.

After completing a subsequent problem in the POGIL activity, the group came back to the question of NaCl mixed in water. Member S2 asked another group if they got option B as their answer. *S4* now argued that "water doesn't break apart" (LN 70). This seems to have moved the group away from option B. In a follow-up response, *S1* agreed with *S4*, stating "the water doesn't break apart. It's C then" (LN 80). *S3*, on the other hand, did not seem convinced because option C "doesn't show H_2O" (LN 81). The group settled on option C after consulting with another group.

Group 3B mainly focused on water as their sole criterion. They initially thought about selecting option C but wanted to see water in the symbolic equation. This focus on the symbolic surface features of the balanced chemical equation made them select option B even though this option did not make chemical sense. Group 3B collectively negotiated what option to select and what counts as chemical justification for their response – in this case, a focus on water.

4.1.1.12. Summary

Results in this section showed individual groups repeatedly using the ideas of ionic solids in water separating into ions and becoming aqueous as justification for their response. There was also appeal to the idea of the ionic compounds not transforming chemically upon dissolving. These chemical ideas (ions, aqueous, chemical change) became normative in group discourses and were used repeatedly by majority of the groups. This met the criteria set forth to answer the first research question: student groups negotiated and developed criteria for what counts as acceptable justification for a given chemical phenomenon. It is apparent from the groups' sociochemical dialogues that they were involved in chemical meaning making and negotiated about what criteria to use for selecting the correct multiple-choice option. Their responses were guided by chemical justification and the use of chemical ideas.

The nature of the groups' sociochemical dialogues provided further evidence that the groups were involved in group thinking. For instance, the sociochemical dialogues were characterized by statement types indicative of collective effort, including confirmatory statements, consensus-checking statements, summary/clarification statements, skeptical questioning, and acknowledgement/support statements.

Given that chemical justifications became normative in each group's discourse and were used repeatedly by large number of the groups as a guide to select multiple-choice options, I examined the patterns of criteria used across the groups. The next section (section 4.1.2) shows the results of this analysis.

4.1.2. Patterns across groups: Across Group-Negotiated Criteria (AGC)

This section provides analysis of patterns across the groups as they attempted to select which balanced chemical equation represents the dissolution of ionic solids in water. One criterion used to determine whether or not an idea become normative was to examine if it was consistently used as a chemical justification by the 10 different groups in the study (code AGC). Table 4.1 below shows the four criteria developed by the different student groups as a guide for selecting the appropriate balanced chemical equation (see summary discussion in the previous section) to represent the dissolution of ionic solids in water. In the table, a positive sign (+) means the group generated and used the indicated criterion whereas a negative sign (-) means the group did not use the indicated criterion.

Table 4.1
Comparison of student-generated criteria use across the groups ('+' *means group used indicated criterion; '-' they did not*).

	Group-Generated Criteria for Dissolving Ionic Solids			
Group	***Separation of salt into ionic species***	***Salt becomes aqueous***	***No chemical transformation occurring***	***Presence/absence of water from the chemical equation***
1A	+	+	–	+
1B	+	+	–	–
1C	–	–	–	+
1D	+	–	+	+
2A	+	+	+	+
2B	+	+	–	+
2C	–	–	–	–
2D	+	–	+	+
3A	+	+	–	–
3B	–	–	–	+

Three of the four criteria described in Table 4.1 (separation of ionic salts into ionic species, becoming aqueous, and absence of chemical change) represent physical properties of dissolving ionic compounds. The fourth criterion, the absence or presence of water from the representative chemical equation, focused more on the symbolic features of the chemical equation. These ideas (ions, aqueous, chemical change, and water) became normative in the students' discourse and were repeatedly used both within and across groups. As can be seen in the table, there are similarities and differences among the groups. These include,

- Seven of the ten groups (1A, 1B, 1D, 2A, 2B, 2D, and 3A) developed and used the idea that dissolving ionic solids separate into ionic species as criterion while three groups (1C, 2C, and 3B) did not.
- Five of the ten groups (1A, 1B, 2A, 2C, and 3B) developed and used the idea that ionic salts become aqueous as criteria while the remaining five (1C, 1D, 2B, 2D, and 3B) did not.
- Only three groups (1D, 2A, and 2D) used lack of chemical transformation or change as criterion to justify their response.
- One group (Group 2C) failed to develop any criterion.
- With the exception of Group 2C, all other groups developed criteria. For Group 1C and Group 3B, water was their only criterion.

The fact that similar ideas were used by the different groups suggested these ideas (ions, aqueous, chemical change, and water) became normative and was used as chemical justification for explaining which equation to represent the dissolution of ionic compounds in water. This finding meets the criterion set forth in chapter 3 and discussed in the opening remarks of this chapter: An idea becomes normative if different autonomous groups develop and use similar criteria to explain the same chemical phenomenon. As can be seen in Table 4.1, this appears to be the case with respect to the dissolution of ionic compounds in water. The next two subsections (4.1.2.1 and 4.1.2.2) examine patterns of criteria use across the groups.

4.1.2.1. Patterns of criteria use – focus on symbolic features in equations

Eight of the ten groups in the study used water as criterion, often in combination with other criteria (Table 4.1). When groups focused on water, they were using it either as exclusionary criterion (water did not change or chemical equation does not show water) or as a confirmatory criterion (chemical equation shows water therefore must be the correct option). To illustrate this point, let's revisit the sociochemical dialogue of Group 1C whose only criterion was water (Table 4.1). Their dialogue was initially shown as Figure 4.3 but the relevant section is reproduced here as Figure 4.11.

83	S1: For one thing it's *[option B]* the only one you're adding water to. The other ones aren't adding water to it. They are have an equation without water
84	S3: It's definitely not D and E. I don't think it's A or C because they don't have the water in the equation
85	Okay [*group chooses B and moves on to the next activity]*

Figure 4.11. Part of Group 1C's dialogue on choosing correct equation for NaCl dissolved in water.

In line 83 of Figure 4.11, *S1* argues option B is the only correct option because "it's the only one you're adding water to. The other ones aren't adding water to it. They have an equation without water". In confirmatory, consensus-checking statement, *S3* uses the presence of water in the equation as confirmatory evidence to rule out the other possibilities stating emphatically "It's definitely not D and E. I don't think it's A or C because they don't have the water in the equation" (LN 84). Here, it may be worthwhile to recall the multiple-choice options the students are discussing. Recall that their task was to select an equation to represent what happens to NaCl dissolved in water.

a. $NaCl\ (s) \rightarrow Na\ (aq) + Cl\ (aq)$
b. $2NaCl\ (s) + H_2O\ (l) \rightarrow 2HCl\ (aq) + Na_2O(aq)$
c. $NaCl\ (s) \rightarrow Na^{+}(aq) + Cl^{-}(aq)$
d. $NaCl\ (s) \rightarrow Na^{+}(s) + Cl_2^{-}(s)$
e. $NaCl\ (s) \rightarrow Na^{+}(s) + Cl^{-}(s)$

In Figure 4.11, members of Group 1C focused on the presence of water in option B and used it as confirmatory evidence of why option B is the only correct option. Member *S1*'s claim that "it's the only one you're adding water to" (LN 83) and *S3*'s statement that "I don't think it's A or C because they don't have the water in the equation" (LN 84) are quite telling!

Similar arguments were made by students in other groups who used water as confirmatory criterion and did not give ground even in the face of contrary evidence presented by other members of the group. Consider, for instance, the discourse from group 1D (see Figure 4.4 for the full discourse)

S1**:** What equation do you think it is?

S2**:** The only one that makes sense is B because it's the only one that is adding water

S4: It's not D or E because those are both solids. It can't be those two. B is the only one that makes sense because it's the only one adding the water

This particular dialogue from Group 1D illustrates how students who focused on water used it as confirmatory criterion to justify their response even though the option they were choosing was incorrect. Here, again, we see the students in Group 1D focus on the symbolic features present in option B – the only equation that has water molecules present and shows water adding. It is noteworthy that Group 1C and Group 1D used similar language to justify their responses. Table 4.2 below shows side-by-side comparison of the two groups' dialogue. Notice the similarity of their language as they describe why option B is the only one that makes sense.

Table 4.2
Side-by-side comparison of Group 1C and Group 1D dialogue

Group 1C	Group 1D
"For one thing it's *[B]* the only one you're adding water to. The other ones aren't adding water to it" (*S1*)	"The only one that makes sense is B because it's the only one that is adding water" *(S2)*
"I don't think it's A or C because they don't have the water in the equation" (*S3*)	"B is the only one that makes sense because it's the only one adding the water" (*S4)*

4.1.2.2. Patterns of criteria use – focus on physical properties

Seven of the ten groups in the study used the idea that ionic salts separate into ions when dissolved in water as criterion (Table 4.1). This was the most frequent reasoning groups used to justify their response and selection of which chemical equation to represent the dissolution process. Because students used a molecular model kit in which they simulated the dissolution process of ionic salts by using magnetized NaCl and water molecules which upon mixing dissociate (opposite magnets get attracted to each other), it is feasible the molecular model kit influenced their view. However, the resulting positive and negative charges on the sodium and chloride ions are not reflected in the model. Rather, the model only shows NaCl separating apart when mixed with water molecules. Thus if a student assumes NaCl will dissociate into neutral sodium and chlorine atoms, the molecular model kit did not rule out that as a possibility – unless students equated magnets with the electrons. Hence, while the use of the molecular models might have helped the students, limitations in the model would probably have been inhibiting as well.

Groups that proposed separation of salts into ions were also likely to justify their responses by reasoning that salts become aqueous when added to water. Four of the five groups that used 'aqueous' as a criterion (see Table 4.1) similarly used the separation of ionic solids into ions as a criterion. These two criteria combined describe the physical properties of dissolving ionic solids. The frequency of uses of criteria related to these physical properties is shown in Figure 4.12. Seven groups (1A, 1B, 1D, 2A, 2B, 2D, and 3A) relied on these criteria while the other three groups (1C, 2C, and 3B) focused solely on the symbolic features present in the balanced equation to guide their response.

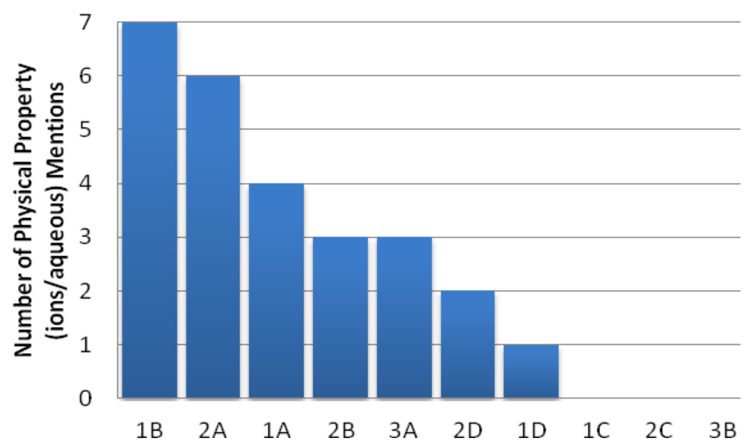


Figure 4.12. Combined number of times descriptions of ions and aqueous were mentioned in group's sociochemical dialogues to justify their explanation of which balanced chemical equation to select. The figure is sorted in terms of descending order (from largest number of mentions to the smallest number).

Analysis of the results in Figure 4.12 suggests a correlation between the use of physical properties as criteria and the nature of the resulting discourse. Groups whose discourse contained three or more mentions of the physical properties (1B, 2A, 1A, 2B, and 3A; Figure 4.12) mostly focused on justifying their reason for why option C of the multiple-choice question was correct or discussed what criteria is critical for selecting the correct answer. In contrast, groups whose discourse contained one or two mentions of the physical properties (2D and 1D; Figure 4.12) had animated arguments and counter-arguments on why option B was incorrect or focused lack of chemical transformations to justify their reasoning of which equation to select.

Groups whose discourse contained frequent mentions of the physical properties as justification were also more likely to choose option C initially as their response than those who did not. For instance, there are only two mentions of the physical properties in the discourse of groups 1D and 2D. Both groups initially focused the bulk of their discourse as to why option B of the multiple-choice question was correct or incorrect (both eventually selected option C as their final response after discussion and dialogue).

4.1.2.3. Summary

Students across all groups used similar criteria to justify their reasoning for an acceptable chemical equation for the dissolution of ionic solids in water. These criteria were either based on the physical properties of dissolving ionic solids or focused on the symbolic presence of water in the equations. The ways in which the groups used these criteria suggested that justifications based on descriptions of the physical properties of ionic salts or the focus on the symbolic features present in the chemical equations became normative across the groups. Interestingly groups who initially used physical properties as criteria ($N = 7$) were more likely to choose the correct response (option C in the prompt question) than groups who focused on water as a criterion ($N = 3$). Some of these groups changed their thinking after the course instructor intervened or after consulting with other groups in the class. At the end of the POGIL activity, eight of the ten groups had the correct option as their final response while two groups had incorrect option (B) as their final response. The two groups that did not change their thinking (2C and 1C) either did not develop any criterion (2C) or only focused water as confirmatory criterion (1C).

4.2. Development of Sociochemical Norms: Criteria for Chemical Conductivity

In activity one and two of the study's instructional unit, the students grappled with how to represent the dissolution of ionic solids in water at the particulate, macroscopic and symbolic levels. Analysis of their sociochemical dialogues in the previous section (section 4.1), focused on selecting an appropriate symbolic equation too represent the dissolution process. Students used the ideas of ions, aqueous, and chemical transformation as criterion for their selection. The groups, however, also used chemical bonding models and information about overall molecular structure as criterion for describing the properties of ionic compounds in solution. This was particularly evident in the groups' sociochemical dialogues with respect to electrical conductivity, the subject of the present section.

The groups' dialogues showed descriptions of molecular structure used as implied criterion that accounts for the electrical conductivity of chemical compounds. Fully delineated episodes from Groups 2A, 1A, 2B, 1C, and 3B are used to illustrate e this finding. While all groups in the study came up with structure-based criteria that were critical for answering questions related to conductivity, I present data for the remaining groups globally in section 4.2.1.11.

4.2.1. Patterns within Groups: Group Negotiated Criteria (GNC) – Conductivity

4.2.1.1. Context

The context for the episodes in this section was as follows. Once students completed activity 1 and 2 of the instructional unit, they proceeded to do conductivity activities (Activity 3 and 4). The following information was shared with the students about conductivity:

Information
When chemical compounds are dissolved in water, they appear to disappear. In reality, the compounds generate homogeneous mixture. One way to test this mixture is through electrical conductivity. The conductance of aqueous solutions can be measured using a devise that displays conductivity values. There are many different devices used for measuring conductivity. One type of device has lights (LEDs) that lit up when a solution conducts electricity. The number of lit LEDs is proportional to the conductivity of the ions in the dissolved solution. (*POGIL Activity, Appendix B*)

Part one of the conductivity activity (Figure 4.13, Part I) asked students to predict whether sodium iodide (NaI, an ionic compound) and sucrose ($C_{12}H_{22}O_{12}$, a molecular compound) when dissolved in water would conduct electricity. Part two asked the students to "explain why the conductivity values of 0.1 M and 0.2 M solutions of sodium chloride (NaCl) are different?" (Figure 4.13, Part II). Discussion of the findings starts with the dialogue from Group 2A.

Part I – Predicting Conductivity

Based on your observations in Activity 1 and 2, ***predict*** whether or not the following compounds would conduct electricity in aqueous solutions. In your response, ***state clearly this compound "will" or "will not" conduct electricity in aqueous solution*** and provide short explanation for your reasoning

1. Solid sodium iodide (NaI)
2. Solid sucrose ($C_{12}H_{22}O_{12}$)

Part II – Explaining Conductivity

Critical Thinking Questions
Explain why the conductivity values of 0.1 M and 0.2 M solutions of sodium chloride (NaCl) are different?

Figure 4.13. Prompts for conductivity activities of the instructional unit. Part I asked students to predict conductivity of NaI and sucrose. Part II asked students to explain differences in the conductivity values of 0.1 M and 0.2 M solutions of NaCl.

4.2.2. Predicting conductivity of chemical compounds – Group 2A, Episode I

Figure 4.14 shows Group 2A's dialogue with respect to the conductivity of sodium iodide (NaI) and sucrose ($C_{12}H_{22}O_{12}$). Subsequent paragraphs describe the findings.

	Dialogue	Code	Comments/Interpretations
86	S1: Well, sodium iodide that would.	*GNC/AGC*	*Initiating move; does not provide reason for response*
87	S3: It has a metal.	*GNC/AGC*	*This is a support statement – Justifies S1's claim.*
88	S1: Yes.	GNC/AGC	*Acknowledgement statement*
89	S3: Okay sodium iodide dissolved in water will conduct electricity because…	GNC/AGC	*In lines 89 – 97, the group repeats the same ideas over*
90	S2: It's ionic and will break into…	GNC/AGC	*and over again; there is appeal*
91	S3: Freely moving ions	GNC/AGC	*to the idea of a compound*
92	S2: Yeah!	GNC/AGC	*being ionic or molecular and*
93	S3: Solid sucrose will not because it won't break and it's not charged to begin with.	GNC/AGC	*also whether the compound has ionic charges or does not.*
94	S2: Yes	GNC/AGC	*Support statement*
95	S1: It doesn't conduct because it doesn't have ions and…	GNC/AGC	*Finishing each other's thoughts*
96	S3: It's a molecular compound, so it's made of atoms not ions	GNC/AGC	*Discussion on atoms vs. ions*
97	S2: And it's not a charged molecule. I wrote that	GNC/AGC	*Mention of charges*

Figure 4.14. Group 2A's dialogue on predicting the conductivity of NaI and sucrose.

In the initiating move of the first episode, *S1* stated, without providing reasoning, that sodium iodide "would [conduct]" (LN 86). *S3* provided a justification in line 87 – "It has a metal." Here, *S3's* use of information about the molecular structure of NaI (the presence of "a metal") reflects an implied criterion for what counts as justifiable reason to explain the conductivity of chemical compounds. In line 88, *S1* acknowledged *S3*'s explanation and proceeded to write down this response, thinking aloud by saying "Okay, sodium iodide dissolved in water will conduct electricity because…" before she is interrupted by *S2*. *S2* who completed *S3*'s sentence as follows – "it's ionic and will break into…" (LN 90). But again another interruption by *S3* occurred – "into freely floating ions" (LN 91). This finishing of each other's thoughts suggests the group was involved in collective group thinking.

In the exchange between *S1*, *S2*, and *S3* in lines 86 – 92 (Figure 4.14), we see the group used molecular structure information ("it is an ionic compound," "it breaks into freely floating ions") as a criterion to account for why NaI conducts electricity. The earlier idea that the compound contained "metal" no longer appeared in the group's ensuing sociochemical dialogue. This does not, however, necessarily mean it was no longer considered as a valid criterion by the group. An alternative explanation could be that once the students identified NaI as ionic compound, it was no longer necessary to mention the presence of the metal since ionic compounds by default contain a metal. This suggests students must be familiar with the molecular structure of compounds in order to come up with criterion that is critical for correctly answering the prompt question.

The criterion the group used to justify why sodium iodide conducts electricity – it is an ionic compound that will break into freely floating ions – should exclude the molecular sucrose from conducting electricity. In lines 93 – 97 (Figure 4.14), we see the group use this criterion to justify why sucrose would not conduct electricity. In line 93, *S3* stated "solid sucrose will not because it won't break and it's not charged to begin with" (Figure 4.14). In line 95, *S1* stated "It [sucrose] doesn't conduct because it doesn't have ions and…," and before *S1* could finish her thoughts, she was interrupted by *S3* who stated "It's a molecular compound, so it's made of atoms not ions" (LN 96). *S2* added to the ongoing discussion – "and it's not a charged molecule" (LN 97). Again, we see descriptions of molecular structure (sucrose "is made of atoms not ions," "it doesn't have ions") used as justification to explain the chemical properties of sucrose.

The repetitive use and appeal to molecular structure information suggests these ideas became normative within the group's dialogue. The group used this structure-based criterion to justify their explanation of which chemical compounds will conduct electricity and which ones will not.

4.2.3. **Explaining differences in conductivity values – Group 2A, Episode II**

Part two of the conductivity activity (Figure 4.13) asked students to explain why the conductivity values of 0.1 M and 0.2 M solutions of sodium chloride (NaCl) are different. Figure 4.15 shows Group 2A's sociochemical dialogue as they attempt to explain why the two solutions have different conductivity values. The dialogue starts after the group read the prompt question.

Dialogue	Code	Comments/Interpretations
98 S3: Molarity values are different.	*GNC/AGC*	*Proposes plausible justification*
99 S2: one is larger	*GNC/AGC*	*S2's "larger" means "more"*
100 S3: So there's more ions to conduct *[instructor interference, class ends]*	GNC/AGC	*Structure-based justification*

Figure 4.15. Group 2A's dialogue on explaining the differences in the conductivity of 0.1 M and 0.2 M solutions of NaCl.

Group 2A's dialogue with respect to the second prompt was rather short. This was mainly an artifact of class management: the group did not get adequate time to complete the activity in a timely manner and rushed through the remaining problems in the second part of the activity. Nevertheless, in the short exchange between *S2* and *S3* in Figure 4.15, we see descriptions of molecular structure ("one is larger" *S2*, LN 99) used to explain why the 0.2 M solution conducts more electricity than the 0.1 M solution ("so there's more ions to conduct" *S3*, LN 100).

4.2.4. **Predicting conductivity of chemical compounds – Group 1A, Episode I**

Figure 4.16 shows Group 1A's sociochemical dialogue as they discussed the conductivity of sodium iodide (NaI) and sucrose ($C_{12}H_{22}O_{12}$) in water.

	Dialogue	Code	Comments/Interpretations
101	S2: The first one would definitely [conduct] because it's ionic	*GNC/AGC*	*Initiating move – justification based on molecular structure*
102	S1: Because the molecule is ionic? Or how do we explain it?	GNC/AGC	*Seeks group consensus*
103	S2: Does it say explain it or just predict?	Procedural	*Procedural talk*
104	S3: Predict with an explanation	GNC/AGC	*Response statement*
105	S4: The charge rule for that one.	GNC/AGC	*Proposes ways to justify response*
106	S2: When freely moving ions are present	GNC/AGC	*Use of particulate-level information*
107	S1: I need to write it on the sheet, so how do you guys want to phrase it?	GNC/AGC	*Seeks group consensus*
108	S4: I'd put that it will conduct electricity in an aqueous solution because it's an ionic bond so the NaI compound would change to Na+ ions and I- ions and the particles would be surrounded by water, which conducts electricity	GNC/AGC	*Follow-up statement: provides justification based on molecular structure information as a reason for response*
109	S1 So, when added to water it will change to ions?	GNC/AGC /SST	*Skeptical questioning – could signal change in thinking*
110	S4: Yeah. For the second one do we think it will conduct or won't conduct?	GNC/AGC	*Asks for group clarification*
111	S2: I don' think it would because it's a molecular compound	GNC/AGC	*Provides structure-based argument for why suggestion is correct*
112	S3: It will stay together	GNC/AGC	*More structure-based evidence*
113	S4: Yeah		*Acknowledgement/support*
114	S1: So, the second one will not conduct electricity?	GNC/AGC	*Group consensus-checking statement*
115	S2: I kind of did an experiment like this in high school and it was like this	Side Talk	*brings in previous experience*
116	S1: Because it's a molecular compound	GNC/AGC	*Group consensus-checking*

and won't separate?		*statement*
117 S4: Yeah	GNC/AGC	*Acknowledgement statement*
[Whole class interruption by course instructor]		
118 S4: I was saying it was a molecular compound and it won't separate into ions when water is added. It will stay a compound	GNC/AGC	*Response statement; affirms group response*
119 S1: That sounds good	GNC	*Acknowledgement statement*

Figure 4.16. Group 1A's dialogue on predicting conductivity of NaI and sucrose.

In the initiating move of the episode, *S2* stated "the first one [NaI] would definitely [conduct] because it is ionic" (LN 101). *S2* justified her reasoning of why NaI would conduct electricity based on molecular structure information ("because it is ionic"). *S1* who was the group's recorder asked for clarification: "because the molecule is ionic?" (LN 102). *S1* refers to NaI as "the molecule" and asked if "the molecule" being ionic was sufficient to explain why NaI would conduct – "how do we explain it?" (LN 101). Clearly in addition to developing criteria that would help them determine which molecules will conduct and which ones will not, it is evident from the group's dialogue that they were involved in group thinking.

In line 105 of Figure 4.16, *S4* suggested using "the charge rule" as explanation for why NaI would conduct electricity. Here *S4* referred to the presence of positive charges in sodium ions and negative charges in iodide as the "charge rule." This was further described by *S2* who stated in a follow-up move in line 106 "when freely moving ions are present –" (LN 106) although she was interrupted before she could finish her thought. *S4*'s suggestion of "to use the charge rule" appears to have prompted *S2*'s response in line 106. *S1* asked for a group consensus: "I need to write it on the sheet, so how do you guys want to phrase it?" (LN 107). *S4* responded by saying "I'd put that it will conduct electricity in an aqueous solution because it's an ionic bond so the NaI compound would change to Na+ ions and I- ions and the particles would be surrounded by water, which conducts electricity" (LN 108). Clearly *S4* had a good grasp of conductivity, as evidenced by her reference to NaI dissociating into charged particles which when surrounded by water will conduct electricity. In line 109, *S1* asked skeptically "So, when added to water it will change to ions?" *S4* responded by saying "Yeah" (LN 110).

In the exchange in lines 101-110, all members of the group participated in the ongoing dialogue (*S3*'s contribution is limited to one line (LN 104) though an important one that resulted extended discourse). With respect to NaI, there are two ideas which the group comes back to: 1) there is an ionic bond in NaI and 2) there will be freely moving ions when the ionic NaI is in aqueous environment. The group uses both of these ideas as criteria to justify their response with respect to sodium iodide (NaI).

The group's discourse with respect to sucrose was initiated by *S4* in line 110 of Figure 4.16 who asked "for the second one [sucrose] do we think it will conduct or won't conduct?" *S2* responds by saying "I don't think it would" (LN 111) and provided structure-based justification for her reasoning "because it's a molecular compound" (LN 111). *S3* provided further structure-based justification – "it [sucrose] will stay together" (LN 112). *S4* acknowledged the conclusions her colleagues reached by simply stating "Yeah" (LN 113). Here we see the group provide justifications for their responses based on molecular structure information (i.e., compound stays together; it's a molecular compound). In lines 110 – 113 there was no mention of "freely floating ions" or "the charge rule" – the ideas the group associated with sodium iodide (NaI).

The group's repetitive use and appeal to molecular structure information suggests structure-based reasoning became normative within the group's dialogue and using these structure-based reasoning to justify their explanation of why NaI would conduct electricity and while sucrose would not. In lines 114 and 116, *S1* checked for group consensus "so, the second one will not conduct electricity" and the reason for that explanation "because it's a molecular compound and won't separate?" *S4* confirmed this conclusion when she states "yeah" (LN 117). *S1*'s consensus-checking statements (LN 109, LN 116) reframed the group's responses in terms of structure-level descriptions ("when added to water it will change into ions?", "it's a molecular compound"). Thus, whether discussing sodium iodide or sucrose, the group justified their explanations with structure-based reasoning.

4.2.5. **Explaining differences in conductivity values – Group 1A, Episode II**

Figure 4.17 shows Group 1A's response with respect to the second prompt question related to the conductivity.

Dialogue	Code	Comments/Interpretations
120 S1: Isn't the 0.2 more concentrated?	*GNC/AGC*	*Information seeks move – proposes plausible explanation*
121 S2: Yeah, there are more ions freely moving	*GNC/AGC*	*Support statement that provides chemical justification – reframes argument in terms of structure info*
122 S1: What did you want me to put on the explanation part? The 0.2 mole solution is more concentrated	*GNC*	*Checks for group consensus*
123 S S4: How do you calculate the ion concentration? I guess I'll figure that out later	GNC/AGC	*Information seeking move – students were under time pressure at this point of their meeting*

Figure 4.17. Group 1A's dialogue on explaining the differences in the conductivity of 0.1 M and 0.2 M solutions of NaCl.

The group initially used mathematical reasoning (“isn’t the 0.2 [molar solution] more concentrated?”)(LN 120) to account for the increased conductivity of the 0.2 M sodium chloride solution. However, the group reframed the mathematical justifications in terms of what that means chemically – “there are more ions freely moving” (LN 122). Thus there was appeal to structure-based information to justify explanations of chemical properties of ionic solids in aqueous environment. Therefore Group 1A used structure-based reasoning to justify their response as to why NaI will conduct while sucrose will not. But, in addition to structure-based reasoning, the group also used mathematical reasoning to describe the differences in conductivity values of two different NaCl solutions.

4.2.6. Predicting conductivity of chemical compounds – Group 2B, Episode I

Group 2B had the most intensive dialogue with respect to predicting the conductivity of sodium iodide and sucrose. Figure 4.18 shows the group’s sociochemical dialogue (given the length of the episode, codes and short commentary are omitted from this figure).

	Dialogue
124	S1: I would say this would conduct electricity because I’m pretty sure salt water conducts electricity better than.. .(mumbled response)… water. But anyway…
125	S3: This is sodium iodide.
126	S1: Still a salt.
127	S2: Solid sucrose. I don’t think sucrose will.
128	S3: No, because it’s not an ionic.
129	S2: It’s molecular.
130	S3: That’s ionic, but this is…
131	S2: It’s molecular.
132	S1: Well sucrose is just sugar. Do you think sugar would conduct electricity?
133	S2: No.
134	S1: You don’t?
135	S2: Sugar? No, I don’t think so.
136	S1: Okay, write that.

137 S2: Sucrose wouldn't. It has nothing.
138 S1: I don't think… water molecules will still be touching no matter what and water conducts electricity.
139 S2: Right, but….
140 S1: It might not be as good, but I still think it might. I don't know.

[At this point a whole class discussion ensued; after the discussion, groups went back to small group discussion]

141 S1: It will because of free moving ions.
142 S2: Free floating ions.
143 S3: Sucrose wouldn't have any ions because it's molecular.

Figure 4.18. Group 2B's dialogue on predicting conductivity of NaI and sucrose.

In the initiating move of the episode, *S1* stated sodium iodide (NaI) "would conduct electricity because I'm pretty sure salt water conducts electricity" (LN 124). Here, *S1* made a link to prior knowledge she holds about the nature of salt water – "salt water conducts electricity." When *S3* stated "this is sodium iodide" (LN 125), *S1* responded by saying "still a salt" (LN 127). At this point of their dialogue the group did not appear to develop any criteria with respect to electrical conductivity other than *S1*'s proclamation that salt water conducts. Although *S3*'s statement "this is sodium iodide" hinted at structure-based justification, it is hard to tell what she meant without further elaboration in her statement. S2's move that "I don't think sucrose will" (LN 127), gave *S3* an opportunity to reframe the discourse in terms of justifying explanations by using structure-based justification – "No, because it's not an ionic" (LN 128). *S2* provided support statement for *S3*'s view that sucrose will not conduct by using another structure-based justification – "it's molecular" (LN 129). *S3 and S2* continued with this line of reasoning, completing each other's statements and arguing "That's ionic [NaI] … but this [sucrose]" (*S3*, LN 130) and "it's molecular" (*S2*, LN 131).

The group's discourse on the electrical conductivity of sucrose elicited series of exchanges in which members argued and counter-argued whether it will or will not conduct. This discourse was mainly driven by the contrary point of view held by *S1* who appears to think sucrose would not because "sucrose is just sugar" (LN 132). One can infer from this statement that *S1* thinks sugar conducts electricity. Her previous suggestion that NaI will conduct because "salt water conducts" (LN 124) and her new claim that sucrose will since it's "just sugar" (LN 132) is due to preconceived misconceptions *S1* holds about electrical conductivity. This interpretation is strengthened by *S1*'s claim in line 138 in which she explains that "water molecules will still be touching no matter what and water conducts electricity" in response to *S2* who argued "Sucrose wouldn't. It has nothing" (LN 137). *S2*'s statement "it has nothing is probably referring to the lack of freely floating ions in the solution – an idea that become normative in their discourse. The exchange between *S1* and *S2* is rather illuminating. Let's examine this short exchange, which proceeds as follows, more closely.

> ***S1***: Well sucrose is just sugar. Do you think sugar would conduct electricity?
> ***S2***: No
> ***S1***: You don't?
> ***S2***: Sugar? No, I don't think so
> ***S1***: Okay, write that
> ***S2***: Sucrose wouldn't. It has nothing
> ***S1***: I don't think… water molecules will still be touching no matter what and water conducts electricity
> ***S2***: Right but …
> ***S1***: It might not be as good, but I still think it might. I don't know

It is apparent from this dialogue *S1* believes anything in water will conduct electricity – "water molecules will still be touching no matter what and water conducts electricity." When *S2* responds "right but …," and *S1* interrupted her and argues "it might not be as good but I still think it might. I don't know." *S1*'s experience is likely informed by everyday life experiences (e.g., if you drop a hairdryer in the bath tub you may get electrocuted), one of the new dimensions in the Johnstone-Lesh Model described in chapter 2 (Figure 2.4).

There are two things of interest apparent in the above exchange. First, the exchange reveals how in cooperative learning environment the process of discussing a concept with peers allows for instant feedback that can lead to shifts in student thinking and understanding (Smith, 1987; Hollabaugh, 1995). Here, *S1*'s position involves from being convinced that sugar will conduct to second guessing herself – "I still think it might … I don't know" The instant feedback and the verbalization of their thinking forced the students to confront each other's views and created controversy that forced them to negotiate and dialogue. Secondly, although chemists often focus on particulate, macroscopic, and symbolic representations in the teaching of chemistry, the exchange reveals the importance of "relevance" as an important representational element. The use of sucrose and table salt revealed *S1*'s misconceptions and the resulting dialogue created that an opportunity for her to rethink about her position. Thus we see the pedagogical consequences of cooperative learning in action.

4.2.7. **Explaining differences in conductivity values – Group 2B, Episode II**

Figure 4.19 shows Group 2B's response to the second prompt on the chemical conductivity activity – explaining differences in the conductivity values of 0.1 M and 0.2 M sodium chloride solutions.

Dialogue	Code	Comments/Interpretations
144 S2: They're different because there are different amounts of ions, right?	GNC/AGC	*Justification based on information present*
145 S1: Well more sodium chloride makes more ions, which will produce more free floating ions.	GNC/AGC	*Acknowledgement/support statement; structure-based justification*
146 S3: Be more conductive. An increase in the conductivity.	GNC/AGC	*Direct connection between information and outcome*

Figure 4.19. Group 2B's dialogue on explaining the differences in the conductivity of 0.1 M and 0.2 M solutions of NaCl.

Group 2B's discourse, as shown in Figure 4.19, was short and to the point. In line 144, *S2* explained that the two solutions have different conductivity because "there are different amounts of ions." This appears to be a case of mathematical reasoning – the student made a direct connection between the conductivity behavior of chemical compounds and the amount of ions present in solution. It is very evident that the student is using structure-based justification to explain the chemical conductivity of ionic compounds. *S1*, in line 145, acknowledged S2's conclusion while S3, in line 146, made the leap to free floating ions resulting the solution to "be more conductive." Thus, the students were using structure-based explanation to justify why one solution will be more conductive than another.

4.2.8. **Predicting Conductivity of Chemical Compounds– Group 1C, Episode I**

Group 1C used structure-based information to justify their predication of whether NaCl and sucrose will conduct electricity. Figure 4.20 shows the group's sociochemical dialogue.

	Dialogue	**Code**	**Comments/Interpretations**
147	S3: Sodium iodide would be the same as sodium chloride. It'd have the same ionic charge	GNC/AGC	*Structure-based justification for response; compares NaCl to NaI*
148	S1: Yes. I would say it will because…	GNC/AGC	*Acknowledgement statement*
149	S3: It will conduct electricity.	GNC/AGC	*S3 finishes S1's sentence*
150	S1: Because freely moving ions are present. Sugar dissolved in water…	GNC/AGC	*Provides chemical justification*
151	S1: We're going to say the sodium iodide would make freely moving ions.	GNC/AGC	*Structure-based justification for why NaI would conduct*
152	S2: Molecular compounds?	GNC/AGC	*Again, we see reference to structure-based information*
153	S1: Yeah, those are all… (mumbling). Sucrose, that's sugar and that would do the same thing salt does. Right?	GNC	*S1 appears to hold contradicting view … justified NaI because it had ions, suggests the same for sucrose*
154	S2: Yeah, it would.	GNC	*Provides support statement for sucrose conducting electricity*

155 S1: So, they both will conduct electricity.	GNC	*Group consensus checking and follow-up response*
156 S2: I think anything in water would conduct electricity.	GNC	*Incorrect use of structure-based info; due to misconception?*
157 S3: Just like a hyped up acetate.	Procedural	*Not sure what this means*
158 S1: Because you'll have free flowing ions in the water.	GNC/AGC	*Provides justification even though it is incorrectly applied*
159 S2: Should we stop now or go on?	Procedural	*Procedural talk*
160 S1: As long as you made your predictions you can go on. We can read. Are you okay with what we have for six?	Procedural	*More procedural talk*
161 S3: Yeah.	GNC	*group consensus response*
¦	~	*Whole class discussion ensued*
¦	~	*deleted whole class discussion*
162 S2: Because there is not ions in it	GNC/AGC	*S2 appears to shift her thinking!*
163 S1: The charge of electricity cannot pass through. It was all carbon, hydrogen, and oxygen is why.	GNC/AGC	*S1 also appears to change her thinking*

Figure 4.20. Group 1C's dialogue on predicting the conductivity of NaI and sucrose.

Group 1C's discourse was rather revealing. While the group used structure-based justification to explain their predictions, it was also apparent preconceived ideas and misconceptions about the conductivity of chemical compounds in water interfered with the group's prediction. Let's look at the group's dialogue to analyze this and other findings. In the initiating move of the episode, *S3* compared the structure of sodium iodide (NaI) with that of sodium chloride (NaCl), arguing "they would have the same ionic charge" (LN 147) and based on that "will conduct electricity" (LN 149). *S1* completed the structure-based justification of why NaI would conduct when she stated it will conduct "because freely moving ions are present" (LN 150). Therefore the group was using molecular structure information to predict the electrical conductivity of sodium iodide in water. The macroscopic demonstration of sodium chloride allowed them to elucidate structure-activity relationship, comparing how NaI would behave based on their observation of how NaCl behaved.

With respect to sucrose, *S2* asked “Molecular compounds?” (LN 151, Figure 4.20), hinting at the use of structure-based justification to predict the conductivity of molecular compounds. However, while confirming sucrose is a molecular compound, *S1* suggested it will conduct electricity just like salt – “Yeah, those are all… (mumbling). … sucrose, that’s sugar and that would do the same thing salt does” (LN 153). Here, *S1* followed her statement with group consensus checking move – “Right?” (LN 153). *S2* acknowledged this conclusion, stating “yeah, it would” (LN 154). Thus while the group is using structure-based information and seems to be aware of the difference between ionic and molecular compounds, yet they make incorrect prediction based on their preconceived ideas or misconceptions about water conductivity. The next lines in the group’s dialogue make this point rather clear. After appearing to conclude sucrose in water will conduct electricity even though it is a molecular compound, the group attempted to further justify their response as follows (lines 155 – 161, Figure 4.20, for reference purposes I show the number of the lines at the far end of the paragraphs):

S1:	So, they both will conduct electricity.	(LN 155)
S2:	I think anything in water would conduct electricity.	(LN 156)
S3:	Just like a hyped up acetate.	(LN 157)
S1:	Because you’ll have free floating ions in the water.	(LN 158)
S2:	Should we stop now or go on?	(LN 159)
S1:	As long as you made your predictions you can go on. We can read. Are you okay with what we have for six?	(LN 160)
S3:	Yeah.	(LN 161)

We see an interesting exchange in this dialogue. All three students participate in the unfolding dialogue and all contribute to the meaning making process. In line 155, *S1* took the lead in concluding that “both will conduct electricity.” *S2* provided structure-based justification in line 156 as the reason why both will conduct – “I think anything in water would conduct electricity." One can infer from this statement that it is probably due to previously held misconception. The students were aware that sucrose is a molecular compound but because they believe "anything in water" will conduct electricity, they were using molecular structure information to justify their response! When *S2* made the claim that "anything in water will conduct electricity" (LN 156), *S3* responded by saying "like a hyped up acetate" (LN 157). While it is hard to interpret what *S3* meent "hyped up acetate" in line 157, nevertheless it is reasonable to assume "hyped up acetate" is referring to a molecular structure and *S3* is using it as a justification to explain why sucrose will conduct. *S1*, on the other hand, reframed the justifications in terms of ionic charges – "Because you'll have free floating ions in the water" (LN 158). Here *S1* mistakenly assumed sucrose will dissociate into free floating ions in water. The group came to the consensus that both NaI and sucrose will conduct electricity (lines 160 -161).

The above dialogue exemplifies one of the pitfalls of group thinking when all members of a group come to the wrong consensus and no one in the group holds opposing point of view that can challenge the group consensus. In this particular case, there was a whole class discussion (data not shown) which resulted in the group as a whole shifting their thinking and changes their response (lines 162 and 163). I will come back to this whole class discussion and how it influenced Group 1C's response with respect to the conductivity of sucrose in the next section where I discuss shifts in student thinking.

In analyzing Group 1C's dialogue with respect to predicting the conductivity of sodium iodide and sucrose, it was evident that the group largely relied on structure-based justifications to explain their predictions of chemical compounds conductivity of electricity in water. The groups as a whole were collectively involved in the chemical meaning making process, completing each other's sentences and using statement types indicative of group thinking and ideas taken as shared.

4.2.9. **Explaining differences in conductivity values – Group 1C, Episode II**

Figure 4.21 shows the Group 1C's response to the prompt in the conductivity activity asking the students to explain the differences of conductivity values for the 0.1 M and 0.2 M sodium chloride solutions.

Dialogue	Code	Comments/Interpretations
164 S2: Why is it higher? Is it because there are more ions?	GNC/AGC	*Seeks information but also provides justification*
165 S1: Yeah, there is more stuff	GNC/AGC	*Acknowledgement statement that also provides justification*

Figure 4.21. Group 1C's dialogue on explaining the differences in the conductivity of 0.1 M and 0.2 M solutions of NaCl.

The group's discussion was limited to a two-line exchange between *S2* and *S1*. In their simple exchange, *S2* and *S1* justified the higher conductivity value of the 0.2 M solution because it has more ions (lines 164 and 165, Figure 4.21). Thus, the students were using mathematical reasoning here and did not appear to reframe their thinking in terms of chemical reasoning. How did you select which discussions to show?

4.2.10. **Predicting Conductivity of Chemical Compounds– Group 3A, Episode I**

Figure 4.22 shows Group 3A's dialogue with respect to the conductivity of NaI and sucrose.

Dialogue	Code	Comments/Interpretations
166 S2: The first one would because it'd be positive and negative.	GNC/AGC	*Provides structure-based justification for NaI conductivity*
167 S1: That one wouldn't [sucrose]	GNC/AGC	*Claim statement about*

	because … (mumbled)…		*sucrose*
168	S1: Because they are all non-metals? Or there wouldn't be…	GNC/AGC	*Provides justification for why sucrose wouldn't conduct*
169	S2: It's not an ionic bond. They don't break apart into separate ions. Carbon and oxygen are both… oxygen is -2 and carbon… yeah.	GNC/AGC	*Further justifications for why sucrose wouldn't conduct*
170	S3:There isn't a metal bond between ions.	GNC	*Misconception on sucrose?*
171	S1: You need an ionic bond, not a covalent bond.	GNC/AGC	*Acknowledgement statement and group consensus check*

Figure 4.22. Group 3A's dialogue on predicting the conductivity of NaI and sucrose.

The group immediately predicted NaI would conduct "because it'd be positive and negative" (*S2*, LN 166). They, however, had a lengthier discussion on whether sucrose will conduct electricity. The unfolding sociochemical dialogue related to sucrose was laden with structure-based justifications. In line 168, *S1* reasoned sucrose will not conduct "because they are all non-metals?" *S2* responded by saying "it's not an ionic bond. They don't break apart into separate ions" (LN 169). Clearly, the students were using structure-based information to justify their response. The last two lines in the episode strengthen this finding. In line 170, *S3* argued "there isn't a metal between ions" while *S1* summarized the group's reasoning of why sucrose will not conduct electricity in line 171 – "you need an ionic bond, not a covalent bond." The use of ionic bond, covalent bond, presence of charged ionic particles and other structure-based explanations became normative in the group's dialogue to account for the electrical conductivity of chemical compounds.

4.2.11. **Extension to the remaining groups**

I analyzed the data for the remaining groups (1B, 1D, 2C, 2D, and 3B) in a manner similar to procedure described above for groups 2A, 1A, 2B, 1C, and 3A. Table 4.3

summarizes the most frequent justification all the groups used to account for the conductivity of NaI and sucrose. Table 4.4, on the other hand, summarizes the groups' most frequent justifications for the different conductivity values of the 0.1 M and 0.2 M NaCl solutions. The results of this analysis provided further evidence that the groups used structure-based justification to predict whether sodium iodide and sucrose will conduct electricity and to explain the differences in conductivity values for the 0.1 M and 0.2 M solutions of sodium chloride. The following paragraphs will further discuss the findings.

Table 4.3
Summary of groups' most frequently used justifications for predicting NaI and sucrose conductivities in water

Group #	Group's prediction and reasoning of NaI conductivity in water		Group's prediction and reasoning of sucrose conductivity in water	
	Prediction	**Reasoning**	**Prediction**	**Reasoning**
1A	conducts	• It has an ionic bond • NaI would change into Na^+ and Cl^- in water	would not conduct	• It is a molecular compound • It will stay together
1B	conducts	• NaI forms ions • It has ions like NaCl	would not conduct	• Sucrose does not form ions
1C	conducts	• NaI is the same as NaCl – same ionic charge	Would conduct	• Molecular compounds do the same thing salt does
1D	conducts	• It is acting like NaCl • There are freely moving ions	would not conduct	• You have to put energy to break it apart • [it is made of] non-free moving ions
2A	conducts	• it has a metal • It's ionic and will break into ions	Would not conduct	• It won't break; it's not charged • It's molecular compound
2B	conducts	• Na and I will separate in water		• Sucrose is a stable covalent compound • It will not dissolve into
2C	conducts	• Salt water conducts	would conduct	• water molecules will still be touching and water conducts
2D	conducts	• NaI is an ionic compound	would not conduct	–
3A	conducts	• NaI would be plus and negative	would not conduct	• They are all non-metals • There isn't a metal bond between the ions • You need an ionic bond

3B	conducts	• [NaI] will dissolve completely	would not conduct	• If you double the molarity, you double [conductivity] values

As can be seen in Table 4.3, all groups predicted NaI would conduct. Most (7/10) initially predicted sucrose would not conduct. Groups 1C, 2C, and 2D were the exceptions – Groups 1C and 2C initially predicted sucrose will conduct and Group 2D made no prediction. 1C and 2C's predictions were informed, as discussed above, by prior knowledge about electrical conductivity of water, consistent with the "experience/human element" dimension from the Johnstone-Lesh Model.

Remarkably groups in the study used similar language to describe the conductivity of both NaI and sucrose. With respect to NaI, groups used the terms "ionic compound" and different versions of "dissociation into ions" across the board as the reason why this compound would conduct electricity. The groups appeared to provide more details in justifying the reasons for their predication of why sucrose will not conduct. Their justifications ranged from 'it is a molecular compound' to 'there are no free moving ions.' Thus the responses related to the predictions of why sucrose will not conduct appear to be more nuanced than the responses related to sodium iodide. Nevertheless, both responces indicate groups use structure-based justifications to explain their predictions of which compounds will conduct electricity in water.

Table 4.4
Summary of groups most frequently used justifications for explaining the differences between 0.1 M and 0.2 M NaCl solutions' conductivity values

Group #	Group's explanation of the differences in conductivity value of 0.1 M and 0.2 M NaCl solutions
1A	The 0.2 M solution is more concentrated; has more freely moving ions
1B	The concentration [of the 0.2 M] is stronger
1C	It has more ions

1D	0.2 M solution contains more NaCl; It has more freely moving ions
2A	Molarity values are different; one is large, has more ions to conduct
2B	There are different amount of ions; produces more free-floating ions
2C	There are more ions in the 0.2 M solution
2D	There are more NaCl in[0.2 M] solution; It would have higher ions
3A	[The 0.2 M solution] is twice a concentrated; There will be twice as many values
3B	If you double the molarity, you double LEDs [conductivity]

Table 4.4 above describes the groups' responses with respect to what accounts for the differences in the conductivity values of 0.1 M and 0.2 M NaCl solutions. The groups used similar language to explain why the 0.2 M solution is more conductive than the 0.1 M solution. The groups reasoned that (1) the 0.2 M solution is more concentrated, (2) the 0.2 M solution has more freely moving ions, and (3) there are more NaCl in the 0.2 M solution (Table 4.4). This finding fulfills two of the three criteria used in this study to determine whether or not a chemical idea became normative (codes GNC and AGC, page 3 and also chapter 3). These particular criteria were:

- Student groups negotiate and develop a criterion for what counts as acceptable justification for a chemical phenomenon (code GNC).
- Different autonomous groups develop and use similar criteria to explain the same chemical phenomenon (code AGC) and/or,
- Different groups use the same criterion as justification for different topics (code AGC).

The data summarized in Tables 4.3 and 4.4 suggests different groups in the study developed and used similar criteria to explain the differences in electrical conductivity of two chemical solutions and that the different groups used the same criterion as justification for different topics – the ideas of ionic compounds dissociating was used as justification to explain both the dissolution of ionic compounds in water and the electrical conductivity of chemical compounds in water.

Findings in sections 4.1 and 4.2, which dealt with student discourse with respect to the dissolution of ionic solids in water and the electrical conductivity of chemical compounds, suggested ideas became normative within and across groups – that is sociochemical norms were established within and across the groups. In the final section of the chapter, I address how the unfolding of these sociochemical norms influenced individual student understandings.

4.3. Shifts in Student Thinking (SST)

There were two lines of evidence indicating shifts in student thinking and the groups' sociochemical dialogues shaping individual student's conceptions of ionic compounds in solution. The first, discussed under section 4.3.1, was due to confrontations with opposing viewpoints during the groups' sociochemical dialogues. The second, discussed under section 4.3.2, comes from analysis of pre-posttest assessment data not shown yet.

4.3.1. Shifts in student thinking due to confrontations of opposing viewpoints

The first line of evidence showing what appears to be evolution in individual thinking comes from the observation that when students were confronted with opposing viewpoints with respect to both dissolution processes and electrical conductivity, they seemed to be changing their initial thinking. Consider, for instance, the case of *S4* from group 2D. In the particulate drawing portion of NaCl before and after mixing with water in the overall POGIL activity, *S4* stated:

> "The main thing we should notice is that NaCl is broken [*in the model, NaCl was in a lattice format that can easily be separated by hand]*, and it's not a matrix anymore as if it were in a dissolved solution"

Based on this statement, it would stand to reason *S4* understands the process by ionic solids dissolve in solution. However, when discussing which balanced chemical equation represents the dissolution of NaCl in water, *S4* initially thought the correct response would be option B in which a metal oxide (Na_2O) and an acid (HCl) form. He justified the reason for his response because option B "has the 2Na with O because the O stays with it." This illustrates disconnect between what *S4* stated in the particulate drawing exercise and how he represented that process at the symbolic level. For clarity purposes, I reproduce the entire episode from Group 2D below as Figure 4.22.

Group 2D Dialogue

172 S2: Well, it'd have to be mixed because it's mixed with water, but that doesn't make sense [*points to B as answer*]
173 S3: I think it's C because the Na and Cl
174 S4: Is it B or D?
175 S3: It's not B
176 S2: It can't be C because there is no H_2O
177 S3: Does there have to be?
178 S4: This one [*points to B*] has the 2 Na with the O because the O stays with it

179 S3: I think it's just trying to say what happens
180 S4: So you think it's C?
181 S2: Because 2 NaCl makes hydrochloric acid and we don't have that. This one [*points to C*] shows the charge and makes more sense. If not B then I think that

182 S3: So, you think it's C?`

Figure 4.22. Group 2D's dialogue on choosing correct equation for NaCl dissolved in water.

The sum statements *S4* made in Figure 4.22 with respect to the dissolution of NaCl in water can be sequentially mapped as follows:

→ Is it [*option*] B or D?

→ This one [*points to B*] has the 2 Na with the O because the O stays with it

→ So you think it's C?

There is an evolution in *S4*'s thinking (Figure 4.22), from seeking confirmation (LN 174) to making case for option B (LN 178) to giving ground to an alternative possibility

(LN 180). It is also possible to interpret the statement “So you think it’s C (LN 180)?” as uncertainty in his viewpoint. This evolution comes as a result of the unfolding sociochemical dialogue. *S3* immediately rejected B as an option (LN 175) while *S2* suggested there is no water in equation C and therefore it could not be the correct response (LN 176). In line 27, *S2* shifted his thinking and now rejected B on the ground that it shows NaCl making HCl, a scenario the group did not observe when using the 3D molecular model. Note this new assertion is contrary to *S2*’s early position, a shift in his thinking. A controversy is created – *S4*’s ideas, theories, and conclusions are incompatible with those of other members. The multiple opposing views stated in the ensuing dialogue in Figure 4.22 availed *S4* opportunities to shift his thinking, and perhaps created the noted uncertainty (“So you think it’s C?” (LN 180). His shift in thinking became more apparent when the course instructor joined the dialogue (data not shown).

The most vivid example of a shift in student thinking (SST) was illustrated by *S1* in Group 3B (Figure 4.23). This group initially chose option B as their response because this was the only option that showed an equation with H_2O, the criterion the group was working under. I reproduce part of the group’s dialogue here to illustrate this point.

Part of Group 3B’s Sociochemical Dialogue

183 S1: Would it be C? No, we have to do the plus H_2O, so …

¦

184 S4: Water doesn’t break apart though
185 S1: That is true, even though none of the other ones say H_2O
186 S3: Why don’t they show the water?
187 S1: The water doesn’t break apart. It’s C then

Figure 4.23. Partial dialogue from Group 3B's conversation on choosing correct equation to represent the dissolution of sodium chloride (NaCl) in water.

In their initial dialogue shown in Figure 4.23, *S1* was convinced that the correct option was B because they "have to do the plus H_2O" (LN 183). However, confronted with an observation from the model by other members of his group, which showed water molecules remaining intact, he seemed to change his thinking. In line 184 of Figure 4.23, *S4* pointed out "water doesn't break apart though," *S1* responded by saying "that is true, even though none of the other ones say H_2O."(LN 185). In the final line of the dialogue, *S1* abandoned his early selection of option B and declared C to be the correct option: "The water doesn't break apart. It's C then" (LN 187). In my view, this is a clear case of a shift in student thinking brought about by opposing viewpoints or new information contradicting initial position the students held – one of the criteria set forth in chapter three.

4.3.2. Further evidences of Shifts in student thinking – electrical conductivity

The foregoing paragraphs described shifts in student thinking resulting from the discourse related to the nature of dissolving ionic compounds in water. Similarly there were shifts in student thinking when dealing with electrical conductivity of chemical compounds. Let's revisit the discussion of Group 1C with respect to whether sodium iodide (NaI) and sucrose will conduct. In Figure 4.20 in page 47, the group predicted both NaI and sucrose will conduct. They based their reasoning on molecular structure information – NaI is an ionic compound, sucrose is a molecular compound. But despite classifying NaI as ionic and sucrose as molecular, the group suggested "both will conduct electricity" (*S1*, Figure 4.20, p47) because "anything in water would conduct electricity" (*S2*, p47). *S1* further stated "you will have free flowing ions in the water," revealing the misconception that sucrose will dissociate in water! However, the group as a whole changed their thinking after a whole class discussion initiated by the course instructor. The shift in student thinking was apparent in the following exchange between S1 and S2 with respect to the conductivity of sucrose:

> ***S2***: *Because there is not ions in it*
>
> ***S1***: *The charge of electricity cannot pass through. It was all carbon, hydrogen, and oxygen is why*.

Here, members of Group 1C shifted from a stance of "anything in water will conduct" to sucrose will not conduct "because there is not ions in it." The group used structure-based justification for their explanation – *S1* stated, "the charge of electricity cannot pass through. It was all carbon, hydrogen, and oxygen, is why." Regardless of the accuracy of the description, we see structure-based reasoning and a shift in a position from the stance students held initially.

The above cases were prototype examples of similar cases across the groups in which discourse within the groups revealed opposing viewpoints that led to shifts in student stance. With respect to the dissolution process of the ionic salts, much of the discourse resulting shifts in student thinking was related to whether option B of the multiple-choice questions correctly represented the dissolution process. I analyzed all cases where individuals shifted their stand/understanding with respect to option B as a result of the unfolding sociochemical dialogue. Table 4.5 summarizes the most common arguments for and against option B. The first column of the table shows the particular group the students belonged to while the second column shows the particular student who argued for option. The third column shows the arguments against option B from other members of the group. The last two columns show, respectively, the groups' initial choice and whether or not they changed their option following the discourse. The reasoning of the student's response is shown above their statement.

Table 4.5
Student-generated arguments for and against formation of metal oxides and acids from dissolving ionic solids and shifts in student thinking

Group	Student	Arguments for Option B	Arguments Against Option B	Initial Choice	Shift in Thinking?
1C	*S1*	→ ***Equation showing water*** "This should be B because … the fact that it's showing two ions [p*ause*] Plus the H_2O"	–	B	No
	S3	"I don't think it's A or C because they don't have the water in the equation"			No
1D	*S2*	→ ***Equation showing water*** "The only one that makes sense is B because it's the only one that is adding water"	→ ***Salt dissociates into ions*** • "When you add salt to water you get … the dispersal of that" (*S1*) → ***No evidence of chemical change*** • "It doesn't change its composition when you mixed it" (*S3*) • "But it has HCl and the Na is with the O" (*S3*)	C	Yes
	S4	"B is the only one that makes sense because it's the only one adding the water"			Yes
2C	*S2*	–	–	B	No
2D	*S4*	→ ***Metal oxide forms*** "This one has the 2 Na with the O because the O stays with it"	→ ***No evidence of chemical change*** • "2 NaCl makes HCl and we don't have that" (*S2*) • "does there have to be [H_2O]"(*S3*)	C	Yes
	S2	→ ***Equation showing water*** "It can't be C because there is no H_2O"			Yes
3B	*S1*	"Would it be C? No, we have to do the plus H_2O"	→ ***No evidence of chemical change*** • "Water doesn't break apart though" (S1, *S4*)	C	Yes

	S3	"B? It's the only one that has plus H_2O"	(?)

Of the nine students whose data is shown in Table 4.5, 78% (7/9) shifted their thinking while 22% (2/9) did not and the evidence was inconclusive in the case of 1 student (*S3* in group 3B). Interestingly, the cases in which there were no opposing views in the groups' dialogue with respect to option B, mainly in groups 1C and 2C in which all the members agreed with each other that option B was the correct choice, the group as a whole did not change their thinking at the time of the data recording. On the other hand, although many individual students initially chose option B as an appropriate equation showing the dissolution of ionic solids, these individual students shifted their thinking as a result of the unfolding sociochemical dialogue. Group thinking, in this sense, influenced individual understanding and shifts in stand were brought about by opposing viewpoints (a member using "ions" aqueous" ideas as a reason why option B is not correct) or new information contradicting initial position(s) the students held (i.e., water remained intact in the molecular model and therefore option B could not be correct).

4.3.3. Shifts in Student Thinking (SST) revealed by pre-posttest assessment

The second line of evidence indicating shifts in student thinking comes from the analysis of the pre-post assessment. Prior to the POGIL activity, students completed a pre- assessment that asked students to select from multiple-choice options the balanced equation representing the dissolution of magnesium nitrate ($Mg(NO_3)_2$ in water. The day following the POGIL activity, students responded to a similar post-test question about the dissolution of sodium iodide (NaI) in water. The pre-posttest results for these two items are shown in Figure 4.24. The correct response for the $Mg(NO_3)_2$ dissolution was option A of the choices shown; the correct response for NaI was option C.

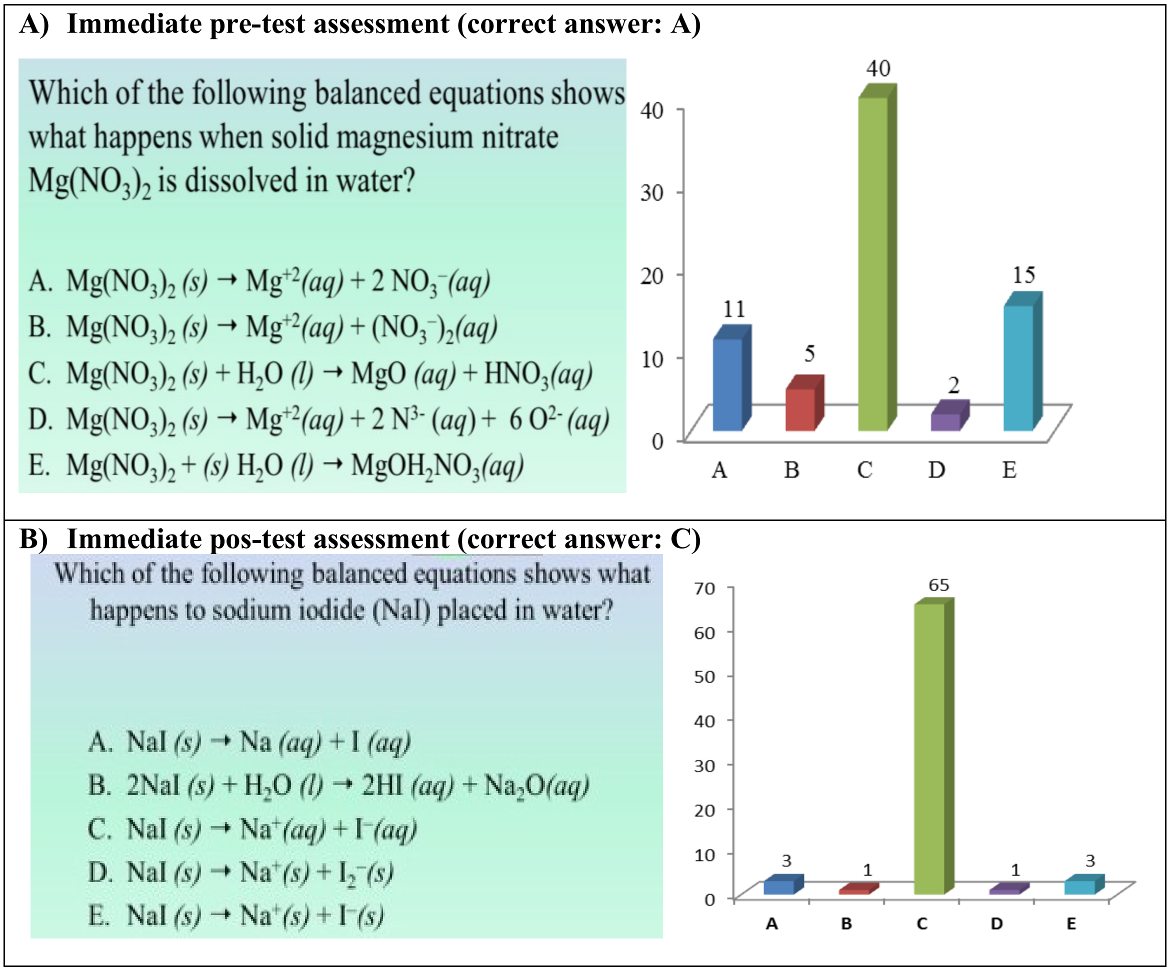


Figure 4.24. Whole class immediate pre-posttest assessment. Students responded to class clicker questions on what happens to ionic solids ($Mg(NO_3)_2$ and NaI) placed in water the day before and after the activity was completed. Number of student making each choice is shown on top of the graphs.

As can be seen in Figure 4.24, most students (40/73, 55%) incorrectly chose option C of the pretest item to represent the dissolution of magnesium nitrate. In this option (option C), the dissolution of magnesium nitrate ($Mg(NO_3)_2$) is shown to result the formation of a metal oxide (magnesium oxide, MgO) and an acid (nitric acid, HNO_3). The formation of a metal oxide and an acid is a common student misconception reported in the literature (Naah & Singer, 2012; Nyachwaya *et al.*, 2011). Only 15% of those responding chose the correct option (A) in which the solid ionic compound dissociated into ions and changed from solid state to aqueous state. The second most popular option, selected by 21% of those responding (15/73), was option E in which the magnesium nitrate was inappropriately combined with water and morphed into a larger individual molecule ($MgOH_2NO_3$). Kern, Wood, Roehrig, and Nyachwaya (2010) reported similar finding in which high school chemistry students inappropriately grouped atoms into larger individual molecules, such as shown in option E. The authors termed this inappropriate grouping of molecules as a "morphed amalgam" (Kern, Wood, Roehrig, and Nyachwaya, 2010, p.168).

The pre-assessment data suggested students' hold two misconceptions about the dissolution process. First, students seem to think that dissolving ionic solids chemically react with water to form an acid and a metal oxide or hydroxide. Secondly, some students think ionic solids combine with water to form one larger molecule. The study by Naah and Sanger (2012) and Kelly and Jones (2007) revealed similar student misconceptions. We reasoned there would be a global impact on students' understanding of the dissolution of ionic solids upon completion of the POGIL activity because of the resulting social interactions in this particular cooperative learning environment and the ensuing sociochemical dialogues as student answer the guided critical thinking questions in the POGIL activity.

The immediate post-test data seems to suggest the POGIL activity had a global impact on the students' understanding with respect to the dissolution of ionic solids (Figure 4.24). Of the 73 students who responded to the immediate post-activity question, 65 (or 90%) chose the correct option in which the salt dissociates into individual ions and changes from solid state to aqueous state (option C of the post-test item in Figure 4.24). Only 1% of those responding (n = 1) chose the option in which a metal oxide and an acid form. This suggests the POGIL activities, on the aggregate, had influenced students' understanding and led to shifts in their stand (Chapter 6 will provide further analysis of the quantitative data and the overall impact of the activity on student learning). The social interactions and the instant feedback students receive as the sociochemical dialogues unfolded led to further elaborations that could account for the observed aggregate impact of the POGIL activities.

The totality of the evidence discussed above (shifting understandings with respect to the dissolution of ionic solids and electrical conductivity of chemical compounds as well as the quantitative evidence showing global impact) suggested the sociochemical dialogues observed in class influenced how students conceived dissolving ionic solids in water. The collective development of understanding, the group's chemical meaning-making in social context and the use of structure-based justification to explain physical and chemical properties availed individual students opportunities to shift their thinking and challenge and provide immediate feedback to members of their social group.

4.4. Chapter Summary

This chapter asked "***How does group thinking during a cooperative inquiry-based activity on chemical bonding shape and influence college students' conceptions of ionic compounds in solution?"*** In response to this question, I described how groups in the study independently developed criteria to justify their explanations with respect to the dissolution process of ionic solids in water and conductivity of chemical compounds. The nature of the discursive practices engaged in by students suggested they were involved in the collective development of chemical justifications to explain their response. The ideas of aqueous, ions, chemical change and what symbolic features were present or absent from chemical equations describing the dissolution of ionic solids become normative in the groups. Furthermore, the groups' sociochemical dialogues revealed groups used structure-based justifications to account for the conductivity of chemical compounds. This too became normative within and across the groups. Thus, with respect to the criteria set forth in chapter three, we can now make the following claims, based on the data discussed in this chapter:

- Student groups negotiated and developed criteria for what counts as acceptable justification for the dissolution of ionic compounds in water and the electrical conductivity of chemical compounds in water.
- Different groups in the study developed and used similar criteria to explain the dissolution of ionic compounds in water and the electrical conductivity of chemical compounds in water.
- Different groups used the same criterion as justification for different topics – the ideas of ionic compounds dissociating was used as justification to explain both the dissolution of ionic compounds in water and the electrical conductivity of chemical compounds in water.

There were two lines of evidence that suggested indicating shifts in student thinking and the groups' sociochemical dialogue influenced individual student's conceptions of ionic compounds in solution. The first came from analysis of data showing what appeared to be evolution in individual thinking when students were confronted with opposing viewpoints with respect to the nature of dissolving ionic solids in water. The second line of evidence came from analysis of a whole class pre-post assessment. The quantitative analysis in the form of pre-posttest assessment following activity completion showed global impact on students' understanding of the dissolution of ionic solids. We reasoned that since students made public their views and encountered opposing ones in the unfolding sociochemical dialogues, this availed them opportunities to shift their thinking (Smith, 1985).

Discourse in the groups was mainly student-generated. This was evident from analyzing the groups' sociochemical dialogues where we see statement types indicative of collective group effort, including consensus checking statements, information seeks moves, confirmatory response statement, and acknowledgement and support statements. However, the groups' sociochemical dialogues were also influenced by teacher's practical moves and interference. The next chapter (chapter 5) describes how the course instructor's moves and interferences influenced students' understandings and the unfolding group dialogues.

CHAPTER 5

"Everybody See That?" The Effects of Teacher-Initiated Discourse on Student Learning

"Why are there warnings on our hair dryers? Why can't I stand in the bathtub and blow dry my hair? Tap water has free moving ions. So let's just look at what happens when I take NaCl and add it to the water ... Now we're definitely conducting electricity. Everybody see that?"

Macroscopic demonstration of conductivity by course instructor

"The use and understanding of a range of representations is not only a significant part of what chemists do – in a profound sense it is chemistry"

R. B. Kozma, 2000, Innovations in Science and Mathematics, p15, Mahwah, NJ: Erlbaum

The previous chapter (Chapter 4) described how student-initiated discourse within the cooperative learning groups in this study shaped and influenced individual student learning. The analysis there mainly focused on ideas that became normative within the groups' microculture and were used to reason and justify chemical explanations about the conductivity of chemical compounds and the dissolution of ionic solids in water. However there were instances in which what became normative in the class and what counted as acceptable chemical justifications was the outcome of teacher-initiated discourse. This teacher-initiated discourse often provided explicit links between the macroscopic, real life experiences, and the particulate modes of the Johnstone-Lesh Model of chemistry representations (see Figure 2.4). For instance, the course instructor often interacted with students to discuss their particulate diagrams and the differences between ions and atoms. It is these encounters between the teacher and the student groups, and other situational aspects of the classroom discourse that is the focus of this chapter. Particularly, I make an attempt to understand how the interplay between the students' experiences and the teacher's practical moves during student-teacher encounters influenced students' understandings and the unfolding sociochemical dialogues. The guiding research question for this analysis was:

<u>Research Question</u> 2: How do teacher's practical moves influence students' meaning making processes and sociochemical norms?

The question arose organically during data collection and analysis when it became evident, as sociochemical dialogues unfolded in the class, that the course instructor was intimately involved in shaping the discourse related to the representational modes of the Johnstone-Lesh Model, particularly the links between the modes.

Results in the chapter are presented in two main sections; the first of which examines the nature of teacher-initiated discourse and the instructional strategies used by the course instructor to link the different representational modes of the Johnstone-Lesh Model. The second section provides a more focused analysis that examines whether there was evidence to suggest teacher-initiated discourse improved student conceptions of dissolving ionic compounds. Selected excerpts from transcribed sociochemical dialogues, based on the nature of teacher-student interactions, provide illustrative examples. The third and final section provides a summary of the findings in the chapter.

5.1. Teacher-initiated discourse on representational forms

5.1.1. Context

Much of the discourse involving teacher encounters occurred during the second activity of the POGIL series when the student groups were generating particulate-level diagrams of dissolving ionic solids or selecting appropriate symbolic-level equations (see ChemActivity 2 in appendix B and Chapter 3 for further descriptions). The other instances in which teacher-initiated discourse occurred frequently were at the beginning and midway of each discussion session when the instructor provided macroscopic observations of what happens to chemical compounds dissolved in water or the electrical conductivity of chemical compounds (see ChemActivity 1 and 3, appendix B). The latter was often preceded by instructor proclamations to the whole class, for example,

> *"Okay, I'm going to have you look back at the front. What I'm going to do for you is activity one. Activity 1 is essentially a macroscopic observation of dissolving materials in water ... Let's start with a little observation. I have this chemical [NaCl] here. How would you describe it?"*

A whole-class discussion often followed the macroscopic demonstrations, with the course instructor initiating class-level discourse. In the following analysis, I noted all instances in which the course instructor was either involved in a dialogical interaction with the students or initiated discourse on her own accord. These instances were analyzed based on what the course instructor was doing. The guiding codes for the analysis were the criteria described in chapter 3. These were:

1. Making links between the different chemical representational modes (i.e., particulate, real life experiences, and the symbolic)
2. Prompts student development of own criteria to describe the nature of dissolving ionic solids

After tagging each recorded POGIL conversation in which the course instructor was involved in the discourse, I examined the instructor's moves (making links between multiple representations and/or prompting criteria development) and how these moves influenced the groups' chemical meaning making process. The following sections describe the results.

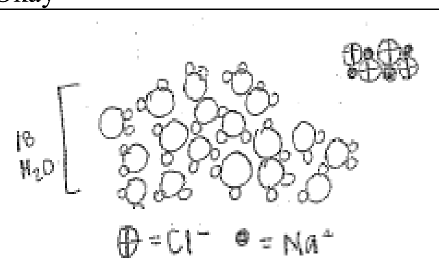
5.1.2. The nature of teacher-initiated discourse on representational modes

There were two kinds of teacher-initiated discourse observed: dialogical and monologic discourse. Teacher-initiated dialogical discourse occurred as a result of directly interacting with students in their small group setting. This often required the course instructor to make several scaffolding moves in response to students' acts and what their particulate drawings revealed about their understanding of the properties of dissolved ionic solids. Monologic discourse, on the other hand, occurred during whole class discussions in which the course instructor first presented data or macroscopic demonstration of a concept and prompted a whole-class discussion on that same concept. The latter was teacher-centered and often involved the teacher making direct links between macroscopic demonstrations and other representational modes. The sociochemical dialogues, in this case, were driven by instructor-expected outcomes. The following paragraphs provide further discussions of each discourse and illustrative exemplars.

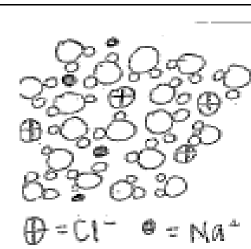
5.1.3. Providing representational links through dialogical discourse

The course instructor often initiated dialogical discourse when interacting with student groups to check their progress and solutions to the Critical Thinking Questions (CTQs) in the POGIL activities, such as the appropriateness of their particulate representations (see appendix B). Her scaffolding moves during these encounters included ways of communicating with students what counts as chemically justified and what counts as acceptable representations of chemical ideas. For instance, in the following episode from group 2A (Figure 5.1), the course instructor made several practical moves that communicated to the students what counts as acceptable particulate representation of NaCl. The group's final particulate drawings of NaCl and water before and after mixing are shown in the figure as a reference point.

1	*Teacher*:	Let's look at your label here. You call it Na and Cl. Are they atoms or are they ions?
2	*Group*:	Ions
3	*Teacher*:	Ions. And how do we show that?
4	*Group*:	Plus's and minus's
5	*Teacher*:	Does that make a big difference in your labels?
6	*Group*:	Yeah
7	*Teacher*:	Okay



Particulate representation of NaCl and H_2O before mixing



Particulate representation of NaCl and H_2O after mixing

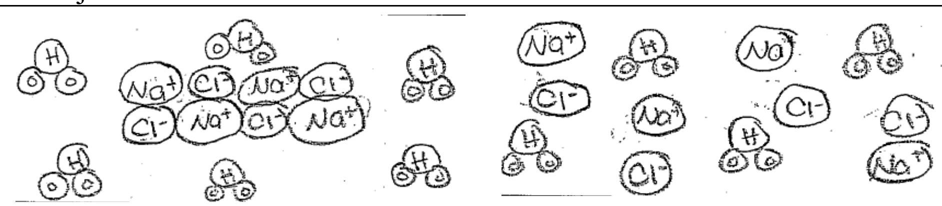
Figure 5.1. Sample dialogical discourse involving course instructor and Group 2A as well as the group's particulate drawings of mixture of NaCl and H_2O before and after mixing

In this particular episode, the teacher noted the students represented sodium and chloride ions in NaCl as discrete neutral atoms (Na, Cl). Her question of "you call it Na and Cl. Are they atoms or ions?" communicated to the students to consider the details of their representation of ionic solids at the particulate level. Her follow-up response in line 3 of "ions" to the group's response of her initial question of whether the sodium and chlorine in NaCl are atoms or ions confirmed the validity of their response. I have coined this discursive behavior as a *confirming move*. Teachers' *confirming moves*, such as the one in line 3, indicate to students that they have recognized the right phenomenon (i.e. ions) and/or confirm the validity of their acts or responses. The course instructor followed this confirmatory move with re-orienting question of "how do we show that?" (LN 3), to which the group responded by saying "plus's and minus's" (LN 4). Teachers' *re-orienting moves* suggest to students the need to modify their response or go in another direction. The re-orienting move in line 3, for instance, allowed the group to modify their initial particulate drawing to the final drawing shown in Figure 5.1. Her question of "does that make a big difference in your label?" in line 5 is a further example of how teacher's practical moves can communicate to students what counts as acceptable representations of ionic solids at the particulate level. The group acknowledged this move with the simple statement of "yeah" (LN 6) and the teacher replied with another confirmatory move (LN 7).

In cases where groups had appropriate particulate representations of dissolved ionic compounds, the course instructor simply provided confirmatory statements validating the group's representation. Figure 5.2 shows one such example involving

Group 1B. As before, the group's final before and after particulate drawings of NaCl and water is shown in the figure.

8	*Teacher*:	You have charges. Good. I'm kind of checking everyone's diagrams here. Pluses and minuses, alright. We got some plus's good job. We still got them over there. Good job.



Particulate representation of NaCl and H_2O before mixing — Particulate representation of NaCl and H_2O after mixing

Figure 5.2. Sample dialogical discourse involving course instructor and Group 1B as well as the group's particulate drawings of mixture of NaCl and H_2O before and after mixing.

The group's particulate drawings, as shown in Figure 5.2, showed solid sodium chloride in a matrix format, with alternating positive and negative ionic centers. Their after drawing, when the NaCl is mixed with the water, showed the sodium and chloride ions in NaCl completely dissociated and randomly distributed with water molecules mostly hydrating the discrete ionic species. Upon observing the group's work, the course instructor made series of confirming moves that validated the group's response (LN 8). She noted the charges on the sodium in the before drawing and stated "you have charges. Good … Pluses and minuses, alright" and noted that the students still used the charges for the after drawing – "we still get them over here" (LN 8). Once she confirmed the group appropriately represented NaCl at the particulate level, she approvingly followed this with a confirmatory response – "Good job." These moves, in addition to serving a confirmatory function, were also communicative in the sense that they signaled to the students what counts as acceptable representation of ionic solids at the particulate level –

"having charges," "pluses and minuses" on both the before and the after drawings, etc. Thus her moves were communicative as well as confirmatory.

Confirmatory, communicative, and re-orienting moves were the main instructional strategies I have thus far described the course instructor using during dialogical discourse. These moves, however, had more than one function. For instance, in addition to redirecting students' responses to what counts as acceptable representations, the course instructor also used re-orienting moves to prompt links to the different representational modes in chemistry. Consider, for example, the following encounter in Figure 5.3 between the instructor and group 2B.

9	*Teacher*:	Let's talk about your model, here. What did we start with?
10	*S3*:	NaCl
11	*Teacher*:	And what is NaCl made out of? Sodium atoms and chloride atoms?
12	*S1*	Ions
13	*Teacher*:	How do we show ions in our diagram?
14	*S1*	Plus and a minus
15	*Teacher:*	So, how would we show that here in our diagram?
16	*S3:*	Sodium
17	*Teacher:*	In your drawing you want to make your Na, not just Na … what do we want?
18	*S3:*	Na^+
19	*Teacher:*	What about these big ones [*pointing to chlorine*]
20	*S3:*	Cl^-
21	*Teacher:*	So when you mixed them together, did you have like heat, cold, anything? Or did they just move around?
22	*S2:*	They just scattered
23	*Teacher:*	They moved around randomly. Kind of attracting, but kind of separating. So, are they still sodium ions and chloride ions? Or are they something different?
24	*S1:*	Same
25	*Teacher*:	In your drawing just note the ions

Figure 5.3. Sample dialogical discourse involving course instructor and Group 2B

The course instructor applied several discursive strategies to scaffold for the students understanding of what counts as appropriate representations of ionic solids at the particulate level. In the initiating move of the discourse, she asked the students what they “started with” to which member *S3* responded “NaCl” (LN 10). In her follow-up response, she asked the students a clarifying question “what is NaCl made out of? Sodium atoms and chloride atoms?” (LN 11). This move communicates to the students what counts as acceptable chemical representation – her rhetorical question of “Sodium atoms and chloride atoms?” (LN 11) signals to the group that “atoms” are not to be used for representing dissolved ionic solids. Member *S1* responded by saying “ions” (LN 12). Her next move in line 13 served both as confirmatory move and re-orienting. The move was confirmatory in the sense that the instructor used the term “ions” in her response to validate the group’s answer and re-orienting in the sense she asked them how “ions” should be shown in particulate diagrams, suggesting to the students the need to modify their response or go in another direction. The instructor’s statement in line 17 – “In your drawing you want to make your Na, not just Na … what do we want?” – can be interpreted as a simple *instructional move* or a further re-orienting move. Instructional moves describe instructional strategies that involve direct telling of what to do next. In this case, the course instructor appeared to tell the students what to do next, “in your drawing you want to make your Na …,” before changing course and asking the students how to represent the Na (“what do we want?”).

The latter parts of the dialogue in Figure 5.3 (lines 21-25) illustrate how the course instructor made concerted effort to link the macroscopic demonstration to particulate representations. In line 21 of Figure 5.3, the instructor asked the students if they noticed anything like heat or cold when they mixed NaCl and the water or if the materials just moved around. Subsequently, in line 23, she further elaborated on the macroscopic observations by stating “they moved around randomly. Kind of attracting, but kind of separating” and then made what I call *linking move* – “so, are they still sodium ions and chloride ions? Or are they something different?” The linking move, in this instance, provided a connection between macroscopic level observations and how to represent that same information at the particulate level. With this move, the instructor emphasized how the material (NaCl) consisted of ionic species no matter the representational mode. Member *S1* acknowledged this linking move by saying “same” (LN 22), which can be inferred to mean that Na and Cl should still be ions at the particulate level. In her follow-up response, the course instructor made an *instructional move* that told the students what to do next – “in your drawing just note the ions” (LN 25). To summarize, the teacher’s practical moves communicated to the students what counted as acceptable particulate representation of dissolved sodium chloride, re-oriented students to appropriate particulate representations, and provided links between macroscopic observations and their particulate drawings.

In addition to linking macroscopic observations to particulate representations, the course instructor similarly build links between macroscopic observations and symbolic representations through dialogical discourse. Consider, for instance, the student-teacher interaction in Figure 5.4 in which the course instructor noticed Group 1D chose option B of the multiple choice options to represent what happens to NaCl dissolved in water. This led to the lively sociochemical dialogue shown in the Figure 5.4.

Directions: Based on your particulate diagrams, which of the following balanced equations shows what happens to sodium chloride (NaCl) placed in water?

a. NaCl *(s)* → Na *(aq)* + Cl *(aq)*
b. 2NaCl *(s)* + H_2O *(l)* → 2HCl *(aq)* + Na_2O*(aq)*
c. NaCl *(s)* → Na^+*(aq)* + Cl^-*(aq)*
d. NaCl *(s)* → Na^+*(s)* + Cl_2^-*(s)*
e. NaCl *(s)* → Na^+*(s)* + Cl^-*(s)*

26	*Teacher*:	Did you observe this? Did you see the Na bonding to an oxygen and a Cl bonding to an H?
27	*S1*:	No, we saw the water stay together.
28	*Teacher*:	The water stayed together. So, does B support that?
29	*S1*	No, it's saying that it all breaks up.
30	*Teacher*:	B does?
31	*S1*	That's what it's saying.
32	*Teacher:*	B is saying you're forming Na_2O and HCl. You're forming H's are connected to Cl's and O's are connected to the Na's. Is that what you observed? Did the O's and H's ever break apart?
33	*Group:*	No
34	*Teacher:*	Oh! Okay. So maybe B isn't supported by that. Think about that one a little bit more

Figure 5.4. Sample of dialogical discourse between course instructor and group 1D

The instructor's initiating move in Figure 5.4 asked the students if they observed, during the physical manipulative phase of the activities, what the chemical equation in option B is showing – formation of a bond between sodium and oxygen and between hydrogen and chlorine (LN 26). As we have seen in chapter 4 (see section 4.1.2.2), the student cohorts in this study often chose option B because they were focusing on the physical features present in the chemical equation and wanted to see the water reacting with the salt. With her question of "did you observe this," the instructor made a *linking move* that connected the students' macroscopic observations of the dissolution model to what the symbolic equation in option B was showing. The move was also communicative in that the nature of her question suggested the combination of Na with Oxygen and H with Cl do not meet the standard of what count as chemically justified and what counts as acceptable representation of dissolved ionic solids. Member *S1* responded by saying "No, we saw the water stay together" (LN 27). We have previously seen the group use water as criterion to select their response (see section 4.1.2.2), so *S1*'s response to the course instructor was not surprising. The course instructor made two simultaneous moves in her response to *S1*, a confirming move and a linking move. Her confirming move, "the water stayed together" (LN 28), validated their macroscopic observation while her linking move "So, does B support that?" attempts to link the macroscopic observation to the symbolic representation.

In line 32 of Figure 5.4, the instructor further stated "B is saying you're forming Na_2O and HCl. You're forming H's are connected to Cl's and O's are connected to the Na's" (LN 32) and follows this with another linking move followed by re-orienting move in the form of question – "Is that what you observed? Did the O's and H's ever break apart?"(LN 32). The group responded by saying "No" and the instructor acknowledged this and made another re-orienting move – "So maybe B isn't supported by that. Think about that one a little bit more" (LN 34). The last comment clearly re-orients the group to a different option than they have selected. Her actions communicate to the group arguments as to why their selection of option B was invalid and, on the other hand, provided opportunities to explicitly link their macroscopic observations to the symbolic equations.

To summarize the main findings in the foregoing discussion, the teacher enacted several practical moves during dialogical discourse with student groups that re-oriented the students to appropriate particulate representations, confirmed the validity of their responses, and communicated to students what counts as appropriate particulate drawings for dissolved ionic materials in water. I have described these moves as *confirmatory*, *re-orienting*, and *communicative*. This classification is based on the methodological framework of learning in the science classroom advanced by Lidar, Lundqvist and Ostman (2005). The authors used what they termed "teachers' epistemological moves" to describe the discursive strategies teachers use when in conversation with students and identified five teacher moves in the context of a science laboratory classroom (1) confirming moves, (2) re-constructing moves, (3) instructional moves, (4) generative moves, and (5) re-orienting moves. I have used modified versions of some of these moves when analyzing the present data, as was the case in the foregoing discussion.

5.1.4. Providing representational links through monologic discourse

Unlike teacher-initiated dialogical discourse, monologic discourses often occurred before students started working on the POGIL activities and involved teacher-provided macroscopic demonstrations of the physical and chemical properties of materials dissolved in water, such as the solubility of ionic solids in water or their electrical conductivity. The instructor's moves in this case involved building links between the students' real life experiences and the properties of ionic compounds. Consider, for example, the encounter in Figure 5.5 between the teacher and students in the second discussion session (Groups 2A – 2D). There are two things to note about Figure 5.5. First, because the teacher spoke more frequently than the students during monologic discourses, the teacher's talk at times is segmented into more than one line (thus lines 35 and 36 in Figure 5.5 are one sentence, with no interference from the class, broken down into two lines for purposes of readability). Secondly, the class often participated in unison in monologic discourse which led to sociochemical dialogues in monologic discourses often alternating between the teacher and the class rather than being between the teacher and an individual student or a group. With this background, we can now look at the teacher's actions during monologic discourse.

35	*Teacher*:	Okay, I'm going to have you look back at the front. What I'm going to do for you is activity one. Activity 1 is essentially a macroscopic observation of dissolving materials in water …
36	*Teacher:*	Let's start with a little observation. I have this chemical here. How would you describe it?
37	*Class:*	Salt. Crystalline
38	*Teacher:*	What kind of salt?
39	*Class:*	Table salt
40	*Teacher:*	NaCl. Also chemically called…?
41	*Class:*	Sodium chloride
42	*Teacher:*	We have crystalline, table salt, sodium chloride. If I were to look at this under a microscope I'd definitely see nice little square type crystals.
43	*Teacher:*	I'm going to take some of these crystals and put them in my container. I'm going to add some water. At some point in your lifetime you've probably done this with table salt. You've taken salt and added water to it [Teacher stirring salt in water]

Figure 5.5. Sample monologic discourse involving course instructor and student groups meeting during the second discussion session

In the sociochemical dialogue shown in Figure 5.5, the instructor initiated the discourse with a macroscopic demonstration of dissolving materials in water (LN 36) and then asked the class how they would describe the chemical she was holding (LN 36). I have come to call her move in line 36 *generative*. Generative moves force students to generate explanations for a given chemical phenomena based on their prior chemical knowledge base and/or real life experiences. This particular *generative move* served two purposes. First, the move linked the students' real life experiences to the class content. Secondly, the nature of her question, "how would you describe that?" signaled to collective meaning making process in which both the teacher and the instructor were participants. The class responded to her generative move by describing the chemical as "Salt. Crystalline" (LN 37), a response to which she followed up with another generative move – "What kind of salt?" (LN 38). Again, this instructor move forced the students to use their chemical knowledge base and real life experience. When the class responded by saying "Table salt" (LN 39), using the household name for salt, she connected this real life response to the chemistry content by saying "NaCl" (LN 40) and made a linking move that built connection between the students' real life experiences and the chemical world – "Also chemically called …?" (LN 40). The class responded by saying "sodium chloride" (LN 41). Thus the instructor made a direct link between students' experiences and the symbolic description of chemical compounds; two of the modes described in the amalgamated Johnstone-Lesh Model in Figure 2.4.

In addition to making direct links between the symbolic world (sodium chloride) and real life experiences (salt, table salt), the instructor also made links between the macroscopic world and the particulate world during monologic discourses. For instance, in line 41 of Figure 5.5, she states "We have crystalline, table salt, sodium chloride. If I were to look at this under a microscope I'd definitely see nice little square type crystals." This creates a scenario in which the students were asked to imagine what the crystals of sodium chloride would look like if magnified. In that sense, this was a linking move that attempted to build a connection between the symbolic and the particular modes of chemistry representations. She also made this linking move in the next sentence in which she connected real life experiences to the macroscopic world – "I'm going to take some of these crystals and put them in my container. I'm going to add some water. At some point in your lifetime you've probably done this with table salt. You've taken salt and add water to it" (LN 43). Here, we see the instructor directly link real life experiences and the dissolution process, emphasizing the fact that *the students have done this with table salt*, that *they have taken salt and added water to it*. These statements were intended to make the students realize the relevance of chemical information to their everyday lives and to go beyond symbolic-based instructional strategies.

The particular monologic discourse episode described in Figure 5.5 did not end there. The course instructor subsequently asked the students what happened to the salt she dissolved in the water. This initiated another discourse episode. Figure 5.6 continues the dialogue between the course instructor and the class.

44	*Teacher:*	How do you describe What happens? The word dissolves comes to mind. Why am I doing this [stirring of NaCl in water]? To speed it up a bit. To get the formula and ion units and molecules to start interacting. But, it's still there. Is all of it still there?
45	*Teacher:*	How can I get more of it to go away?
46	*Class:*	Water.
47	*Teacher:*	More water, that's one trick. What's another trick that some of you might know?
48	*Class:*	Heat.
49	*Teacher:*	Heat it. Often, but not always, by heating up the solutions this will work. There wasn't quite enough water, so I added more water and I shake it up and mix it around.
50	*Teacher:*	Eventually back to when you were maybe first developing and seeing things as a young child they would say it disappears. It's gone. But, of course as you develop you start to realize that there's evidence that it has not disappeared. What's some evidence that it did not disappear? If you were at home and did this, how do you test to make sure that it didn't really disappear?
51	*Class:*	Heat it up and boil it.
52	*Teacher:*	You can heat it and I can boil off what?
53	*Class:*	Water.
54	*Teacher:*	If I boil off the water then what's going to be left behind?
55	*Class:*	Salt.
56	*Teacher:*	Is it the same salt that you started with?
57	*Class:*	Yes.
58	*Teacher:*	Okay, so it's a reversible process. What else could you do?
59	*Class:*	Taste it.
60	*Teacher:*	So, you could taste that it was salty. So there's some evidence that it's still there. There is some more evidence, but those are some common pieces we can use.

Figure 5.6. Continuation of the monologic discourse between course instructor and student groups meeting during the second discussion session

We see many scaffolding moves in the dialogue shown in Figure 5.4. In line 44, the course instructor shares with the students what happened when she stirred NaCl in water, how the process can be described as "dissolving" and how the act of stirring gets the formula and ion units and the molecules interact. The instructor, in this case, is sharing information about the dissolution process and what happens when you stir ionic solids in water. The students are at the receiving end of this information, so I have come to call this *sharing move*. In a sharing move, the course instructor is providing information about chemical content to the students. As such, sharing moves are often characterized by "telling" rather than "discussion." After sharing the students with the information about the stirring process, the instructor makes a generative move – "How can I get more of it [the NaCl] to go away?" This elicited responses ranging from adding more water to heating the solution. The instructor then makes another linking move, connecting real life experiences to the dissolution process – "eventually back to when you were maybe first developing and seeing things as a young child they would say it disappears. It's gone. But, of course as you develop you start to realize that there's evidence that it has not disappeared" (LN 50). This, again, allowed her to connect students' real life experiences to the chemical content. She followed this dialogue with a list of generative moves (lines 51 – 60) that forced the students to use their chemical knowledge base and life experiences.

From what I have described thus far, it appears teacher-initiated monologic discourses were mainly characterized by generative, linking, and sharing moves. The dominant voice in the discourse was the teacher who made concerted effort to explicitly connect for the students the multiple modes of the Johnstone-Lesh model of chemistry representations.

5.1.5. Section summary

Analysis of classroom instances in which the course instructor interacted with student groups or the class as a whole revealed two types of teacher-initiated discourse: dialogical discourse and monologic discourse. The instructor's actions during these encounters spoke volumes about her instructional strategies. Here, I adapted the methodological framework advanced by Lidar, Lundqvist and Ostman (2005) to classify what the authors referred to as "teachers' epistemological moves" to describe qualitatively the different practical moves teachers make in conversation with students. Using this methodological approach, I observed seven teacher moves that identified what the teacher was doing during student encounters. Table 5.1 summarizes these moves. These included: communicative, confirming, re-orienting, instructional, generative, sharing, and linking. In general, these moves communicated to the students what counts as chemically justifiable and what counts as acceptable chemical representation of dissolving ionic solids, confirmed the validity of students' acts and responses, provided links between the multiple representational forms of chemistry, and either shared information with the students or forced them to generate plausible explanations based on their chemical knowledge base and/or real life experiences, or provided direct instructions to the students on what to do next.

Table 5.1

Summary of teacher's practical moves identified in this study and their use during teacher-initiated dialogic and monologic discourses

Practical move	Nature of discourse in which move is used		Intent of the move
	Dialogic	Monologic	
Communicative	X	X	Communicated to students what counts as chemically justified and what counts as acceptable representations of chemical ideas
Confirming*	X		Indicates to students they recognized the right phenomenon (i.e. ions) and/or confirm the validity of their acts or responses
Re-orienting*	X		Suggests to students to modify their response or go in a different direction
Instructional*	X	X	Provided direct instructions to students on what to do next
linking	X		Provided explicit links between the different representational modes of chemistry
Generative*		X	Forces students to generate explanations for a given chemical phenomena based on their prior knowledge
Sharing		X	Teacher shares with students information and facts about chemical phenomena

**These moves are modifications of those used in the Lidar, Lundqvist and Ostman (2005) study (see p159 of their study). While the names of the moves are similar, the description of the moves is quite different from the ones in their study.*

As shown in Table 5.1, the course instructor used five of the seven moves during dialogical discourse – communicative, confirming, re-orienting, instructional, and linking. On the other hand, she used four of the seven moves during monologic discourses – communicative, instructional, generative, and sharing. This suggests that different discourses elicit different teacher moves and that the moves are strongly influenced by the nature of teacher-student encounters. As described in the next section, this has implications for student learning, with the moves either enhancing or hindering student learning.

5.2. The effects of teacher-initiated discourses on students' understanding

The foregoing discussion in section 5.1 described the nature of teacher-initiated discourse and the practical moves the course instructor made to communicate to students what counts as chemically justifiable explanation and what counts as acceptable representations of chemical ideas. We similarly saw the interplay between the students' experiences and the teacher's practical moves. The following, then, describes whether or not teacher-initiated discourses impacted students' conceptions of ionic solids dissolved in water.

5.2.1. The effects of teacher-initiated dialogic discourse on student understanding of the nature of dissolving ionic solids

There was evidence to suggest teacher's dialogical discourse positively impacted student understanding of what happens to dissolved ionic solids in water. This claim is based on the observation that there were shifts in student and whole group thinking following teacher's intervention. The following two cases involving Group 1D and 1A illustrate these shifts.

5.2.1.1. Shifts in student thinking – Case 1: Group 1D

Figure 5.7 below shows the course instructor's interaction with Group 1D. This particular dialogue is a revisit of conversation we came across in chapter 4. There, we saw Group 1D choose option B of the multiple choice equations representing the dissolution of NaCl in water as their response. We paid close attention to member *S4* was adamant about option B was the only answer that made sense because it showed the water molecules while the other questions did not show that possibility. In the following dialogue shown in Figure 5.7, the course instructor observed the group selected option B and initiated the following dialogical discourse with members of the group.

61	Teacher:	When you look at NaCl [*points to group's particulate drawings of dissolved NaCl]*, do you get atoms or ions?
62	S1:	ions
63	Teacher:	How do we show that in our diagrams?
64	S1:	Add the charges
65	Teacher:	Yeah, otherwise you're telling me … what's the difference between the atom and an ion?
66	S4:	The number of electrons
67	Teacher:	You're telling me it has all of its electrons, and he's telling me [*another student*] it shouldn't. Well, your guess is right. When you mix it together, is it still the ion? Did you feel any major energy changes, or did it just mover around?
68	S3:	Move around
69	Teacher:	So, should they still be charged in your mixture?
70	Group:	Yep
71	Teacher:	They are still ions
72	S4:	It's C then
73	S2:	Alright [*episode on NaCl ends here*] So, now we have to do the methanol. Take the salt out [*a new episode is initiated*]

Figure 5.7. Sample dialogical discourse between course instructor and Group 1D

In the dialogue shown in Figure 5.7, the course instructor made several practical moves that helped the group understand what is happening at the particulate level (LN 61, LN 63, LN 65, and LN 67) and made links between the particulate and the symbolic worlds (LN 69 and LN 71). Her moves included re-orienting moves (LN 61and 63), confirming moves (LN 65) and linking moves (LN 67, 69, and 71). These scaffolding moves can be mapped out as follows:

Re-orient the group (LN 61) → [*In NaCl*] do you get atoms or ions?

(LN 63) → how do we show that [ion] in our diagram?

(LN 65) → what is the difference between the atom and ion?

Link representations (LN 67) → when you mix together, is it still the ion?

(LN 69) → so, should they still be charged in your mixture?

Confirm responses (LN 71) → They are still ions

These set of scaffolding moves lead to collective shift in student thinking, as evidenced by the groups' confirmatory response of "Yep" in line 70. There was also evidence of shifts in individual student thinking as evidenced by *S4*'s enthusiastic declaration of "it's C then" in line 72. Thus, in this particular episode, we see student thinking shift as the sociochemical dialogue unfolded and as the course instructor communicated to the group arguments as to why their option was invalid (LN 69) and as to what counts as acceptable representation of dissolved ionic solids at the symbolic and particulate level (LN 69).

5.2.1.2. Shifts in student thinking – Case 2: Group 1A

A similar case in which the course instructor communicated to students why certain representations are chemically justifiable and appropriate while others are not occurred during an encounter with Group 1A. Figure 5.8 shows this particular dialogue.

74	Teacher:	I'm going to call you guys on that too. On your label you have a Cl with -2 and then Na with a +2. Did I give it to you as one formula unit, or did I give it to you as a crystal?
75	S1:	Crystal
76	S4:	So, does that mean the charges wouldn't be there?
77	Teacher:	But aren't they still the same particles?
78	S3:	They're still plus and minus
79	Teacher:	They're still plus and minus. Are they +2 and -2? Or are they +1 and -1?
80	S3:	I said +3
81	S1:	I think it's +1
82	Teacher:	It is in that first column and Cl is… yep. And again, I didn't give it to you as a single formula unit. I gave it to you as a matrix, right?
83	Group:	Yeah
84	Teacher:	Specifically, a one to one matrix. So, should the balls be overlapping or just kind of next to each other?
85	S1:	Next to each other

Figure 5.8. Sample dialogical discourse between course instructor and Group 1A

In their initial model, the group used overlapping circles with Na^{+2} and Cl^{-2} inside the circles. Thus there were two errors the course instructor noted: overlapping drawings as if the Na and Cl were sharing electrons and incorrect oxidation states for both ions. In line 74, the course instructor points out that the physical models the students were given was in a matrix format and not a formula unit which is what led the students to incorrectly write Na^{+2} and Cl^{-2} (they assumed the two sodium ions in the model can be represented as Na+2 and the two chloride ions as Cl^{-2}). What we would like to know is if the instructor's discourse impacted the student's learning. The evidence, as described below, seems to suggest that was the case.

In line 76, *S4* wonders if the fact that NaCl was crystals before the mixing means "the charges wouldn't be there" after the mixing. This misunderstanding is what led the students to show dissolved NaCl as discrete neutral atoms. The teacher's re-orienting move of "but aren't they still the same particles" (LN 77) leads to shift in student think – "They are still plus and minus" (LN 78). We also see at the end that the students come to the realization that ionic centers in ionic solids do not overlap, as indicated by the exchange between the teacher and member *S1*:

Teacher: So, should the balls be overlapping or just kind of next to each other?

Response: Next to each other

Figure 5.9 below shows the group's final drawings of NaCl and Water before and after the mixing. I argue the teacher's dialogical discourse improved the group's representational fluency – we no longer see overlapping ionic centers or inappropriate designations of the oxidation states in the group's final model.

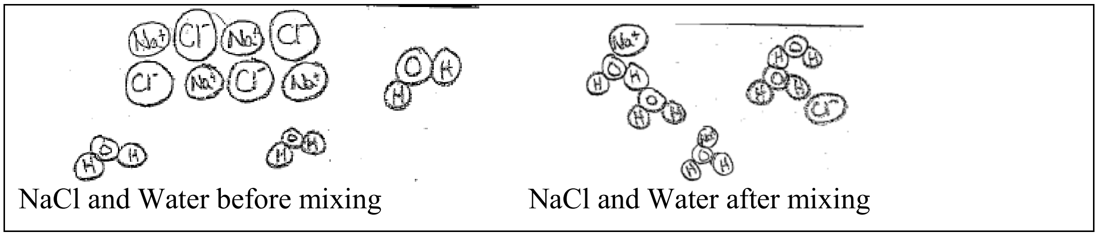


Figure 5.9. Group 1A's final drawings of NaCl and Water before and after mixing them

The nature of teacher's moves and her communicative arguments as to why certain representations were valid and acceptable, while others were not, suggests that teacher-initiated dialogical discourse positively impacted student learning. The same cannot be said about monologic discourse, where there did not appear to be any impact on student learning. The macroscopic demonstrations and the nature of the teacher's moves did not seem to have alleviated student's difficulties understanding the nature of dissolving ionic solids nor were there observed shifts in individual or whole group thinking. The following case involving group 1C illustrates this point.

5.3. The effects of teacher's monologic discourse on student understanding – The case of Group 1C

Much of the sociochemical dialogues discussed in chapter four occurred right after the course instructor macroscopically demonstrated what happens to NaCl placed in water or the electrical conductivity of chemical compounds. Figure 5.10 below shows Group 3B's unfolding sociochemical dialogue following the instructor's macroscopic demonstrations. The group is discussing, with the aide of the molecular models, what happens to NaCl after mixing in water.

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86 S3 So, before mixing the salt… (mumbled)…
87 S1: And there was water everywhere …
88 S2: They're supposed to break apart. Okay, so afterwards
89 S1: It's just one big clump
90 S3: The big chunks from the salt connect to the white, and the small ones connect to the red

91 S2: … Based on the particular diagram which of the balanced equations shows what happens when NaCl is placed in water? I forgot to add the H_2O
92 S1: Would it be C? No, we have to do the plus H2O so
93 S3: B? It's the only one that has plus H_2O.

Figure 5.10. A sociochemical dialogue from Group 3B following instructor demonstration of what happens to NaCl dissolved in water

If the teacher's monologic discourse during the macroscopic demonstration of what happens to NaCl dissolved in water were to have an effect, we would expect the group to recognize that NaCl dissociates into ions in water – the course instructor used the ideas of ions and formula units during her monologic discussion of the dissolution process. You may recall from the earlier discussion in section 5.1.2.2 that course instructor used several practical moves, including linking, generative, and instructional moves, to link the macroscopic demonstration of the dissolution process to what happens at the particulate and symbolic levels. However, the dialogue in Figure 5.10 suggests the students did not understand this linking between the different representations. For instance, in line 89 of Figure 5.10, *S1* suggests that after mixing, "it is just one big clump" and *S3* suggests the NaCl reacts with water – "The big chunks [Cl] from the salt connect to the white [H], and the small ones [Na] connect to the red[O]" (LN 90). Thus, S3 assumes Na will form a bond with O to form Na_2O and Cl with H to form HCl. The instructors' discussion of what happens to ionic solids placed in water did not register with these students – they are using their pre-existing notions of what happens to describe the dissolution of NaCl in water. This observation led me to conclude that the macroscopic demonstrations did not, generally speaking, impact students' understanding of the dissolution process.

5.2.3 The connection between teacher's practical moves and their impact on student learning

The teacher's practical moves differed during dialogic and monologic discourses. During monologic discourse, the teacher used communicative, instructional, generative, and sharing moves. Her moves during dialogic discourses were characterized by linking, communicative, re-orienting, confirming, and instructional. It possible the differences in these moves caused the different impact of the dialogical and monologic discourse on student conceptions of dissolving ionic compounds. The moves in monologic discourse were often of "telling" nature and the instructor's voice was the dominant voice in the dialogue. Such moves did not allow the expected social construction of knowledge among the participants as was the case in dialogical discourse encounters. However, this hypothesis will need further testing and scrutiny beyond what is described in the forgoing pages.

5.3. Chapter summary

In attempt to answer the second research question of the study, *how do teacher's practical moves influence students' meaning making processes and the nature of unfolding sociochemical norms*, I examined the nature of teacher-initiated discourse and the instructional strategies the instructor used to link the different representational modes of the Johnstone-Lesh Model of chemistry representations. Analysis of all classroom instances in which the course instructor interacted with the student groups in this study or the class as a whole revealed two types of teacher-initiated discourse: dialogical discourse and monologic discourse. Teacher-initiated dialogical discourse occurred as a result of directly interacting with students in their small group setting and often required the course instructor to make several scaffolding moves in response to students' acts and what their particulate drawings revealed about their understanding of the properties of dissolved ionic solids. Monologic discourse, on the other hand, occurred during whole class discussions in which the course instructor first presented data or macroscopic demonstration of a concept and prompted a whole-class discussion on that same concept.

During dialogical discourse, the course instructor enacted several practical moves that re-oriented the students to appropriate particulate representations, confirmed the validity of their responses, and communicated to students what counts as appropriate particulate drawings for dissolved ionic materials in water (see Table 5.1). She similarly used dialogical discourse to build connections between the different representational modes of the Johnstone-Lesh Model of chemistry representations.

During monologic discourse, the course instructor was the dominant voice but similarly made several practical moves that provided direct links between the different representational modes in the Johnstone-Lesh Model. Two moves particularly observed during teacher-initiated monologic discourse were generative and linking. Generative moves forced students to explain chemical ideas based on their prior chemical knowledge base or real life experiences. Linking moves provided connections between the different representational modes of chemistry.

Analyzing how teacher-initiated discourses effected student conceptions of dissolving ionic solids suggested dialogical discourses positively impacted student understanding while the effects of monologic discourse were not that apparent. This difference in effect may be accounted for by the nature of teacher's practical moves during the discourses. During dialogical discourse, the teacher was often co-establishing meaning of chemical ideas with the students y re-orienting them, confirming the validity of their responses, or provided direct links for them whereas she was the dominant voice during monologic discourses – often sharing information or asking students to answer direct questions.

This chapter, as in the one before, showed the value of classroom discourse and how the unfolding sociochemical dialogues, whether student-initiated or teacher-initiated, influenced students' conceptions of what happens to ionic solids dissolved in water. I have thus far examined the effectiveness of these social interactions on student understanding qualitatively. The next chapter (chapter 6) examines the effects of group thinking and classroom sociochemical norms on student learning quantitatively.

CHAPTER 6

Instructional Pedagogies and Student Learning

"Learning is not the transfer of material from the head of the teacher to the head of the learner intact, (but) the reconstruction of material in the mind of the learner."

"It is idiosyncratic reconstruction of what the learner … thinks she understands, tempered by existing knowledge, beliefs, biases, and misunderstandings."

Alex H. Johnstone (1997). Chemistry Teaching – Science or Alchemy? *J. Chem. Ed.,* 74, 262 - 268

Chapters 4 and 5 described how sociochemical norms and class discourse shaped and influenced the ways in which students conceived the nature of ionic solids in water. Much of the emphasis in those chapters was the nature of classroom discourse and how group thinking in the context of social interactions affected individual student learning. The emphasis was on the sociochemical norms and unfolding sociochemical dialogues. In this chapter, I discuss the third research question: ***How do cooperative inquiry-based pedagogies, namely POGIL pedagogy, impact student understanding of the nature of***

ionic compounds in solution? The emphasis in this case is on the POGIL activities and their ability to improve student learning, not the sociochemical dialogues triggered by the activities.

Recall one of the aims for designing the instructional activities in this study was to target commonly held student misconceptions related to ionic bonding (Taber, 1998; Naah and Sanger, 2012). There was also desire to emphasize representational fluency and students' abilities to make connections between multiple representational levels (Johnstone, 1991). Chemistry instruction in its present form, unfortunately, often forces students to memorize material presented at the symbolic level (Kozma, 2005), with didactic lecturing as the main mechanism for content delivery. However, as Alex Johnstone points out in the opening remarks of this chapter, "learning is not the transfer of material from the head of the teacher to the head of the learner intact, but the reconstruction of the material in the mind of the learner" (1997, p264). This "reconstruction of the material in the mind of the learner" is the intent of the larger POGIL project. Here, I examine specifically how the POGIL activities affected students' representational fluency and thinking about ionic bonding.

The chapter is organized by presenting data in three sections. The first section (Section 6.1) describes symbolic-level data in which students selected from multiple-choice pre-posttest questions correct responses that represent what happens to ionic compounds placed in water. Main data in this section was collected immediately before and after the POGIL activities. While the immediate pre-posttest data is the center of data analysis, findings are complemented by data from early-pretest as well as findings from chapter 4 – group sociochemical dialogues. Analyses in this and subsequent sections are presented from a general to a case-specific manner, moving from class-level to group-level analysis focused on the 10 different groups. The second section of the chapter (Section 6.2) analyzes students' particulate-level understandings of what happens to ionic compounds placed in water. Data for this section came from student responses in an open-ended early-pretest and delayed-posttest drawing tasks. Both this section and the previous section describe student misconceptions about the nature of dissolved ionic solids and the extent in which the POGIL activities were able to correct these misconceptions. The third section (Section 6.3) compares the immediate pre-posttest data with delayed-posttest data to address issues of retention and transfer. Analysis in Section 6.3 mainly relies on symbolic-level data (i.e., pre-posttest data).

6.1. Analysis of symbolic-level data

6.1.1. Context

Recall the POGIL activities in this study were administered in the middle of the semester (the 7th week of course instructions) when the students were learning about solution chemistry. At that point of the semester, the students had already been taught about the differences between ionic and molecular compounds, how to write and balance chemical reactions, chemical stoichiometry, and the fundamentals of solution chemistry (molarity, concentration, etc.). Thus the POGIL activities used in this research were administered with the understanding that students should have the necessary prerequisite knowledge to successfully complete the activities.

Also recall that there were a cluster of six questions administered a day before and after the POGIL exposure in order to capture the influences of students' prior knowledge, including content they might have learned in the first six weeks of instruction. The immediate pretest items (see chapter 3 for details) involved the dissolution of the ionic solids potassium sulfate (K_2SO_4), magnesium nitrate ($Mg(NO_3)_2$) and calcium chloride ($CaCl_2$). The immediate posttest items involved the following sodium salts of sulfate (Na_2SO_4), chloride (NaCl) and iodide (NaI). As was described in chapter 3, these items were isomorphic structurally and contained common salts including household salts (i.e., table salts). Other salts, such as magnesium bromide ($MgBr_2$), were included in the delayed-posttest assessment. The immediate pre-posttest questions assessed student understanding of what happens to dissolved ionic solids *at the symbolic level*. The following section provides analysis of these data (a small portion of this data was discussed at the end of chapter 4 when describing the effects of sociochemical dialogue on student thinking. This chapter provides more detailed analysis of this earlier data). Discussion of the findings starts with whole class-level data analysis.

6.1.2. Class-level analysis

Analysis of whole-class performance ($N = 74$) revealed that the percentage of students who chose the correct balanced equations for dissolving ionic solids was significantly higher in the immediate post-POGIL assessment (Figure 6.1). In the immediate pre-POGIL assessment, only 15% of those responding selected the correct equations showing the dissociation of K_2SO_4 and $Mg(NO_3)_2$ into individual aqueous ions. In contrast, in the immediate post-POGIL assessment, 80% selected the correct equation for the dissociation of Na_2SO_4 and 90% did so with respect to NaCl while 89% did so with respect to NaI. It thus appears the class as a whole performed at a much higher level in identifying symbolic-level equations for dissolving ionic compounds upon completing the POGIL activities.

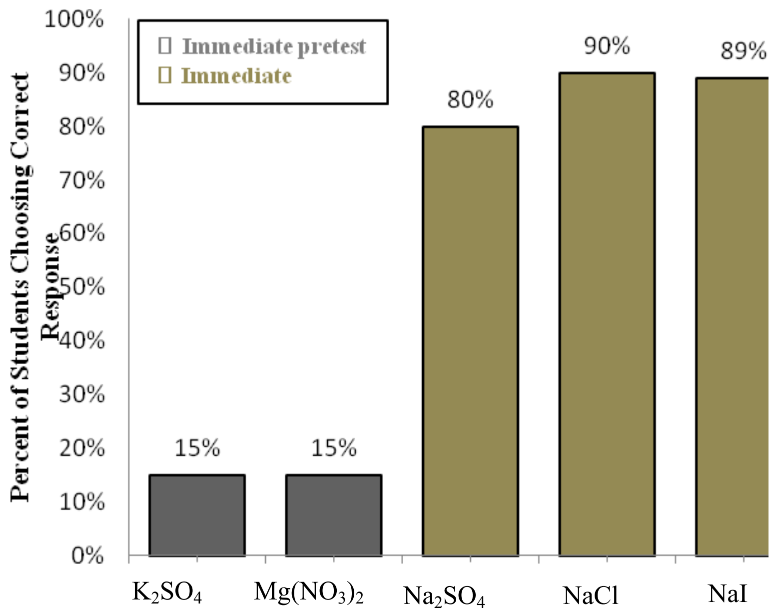


Figure 6.1. Whole-class immediate pre-posttest data showing frequency of students who chose, from multiple-choice options, the correct options in which solid ionic salts dissociated into individual aqueous ions. The immediate pre-posttest data was collected a day before and after the day the POGIL activities were completed.

The percent of students who selected the correct response with respect to $CaCl_2$, the third item in the immediate pre-test, was much higher (59%, data not graphed) than it was for the other two items in the pretest, K_2SO_4 and $Mg(NO_3)_2$. This was mainly an artifact of the test: the multiple-choice options in this question were particulate drawings without the misconceptions shown for items K_2SO_4 and $Mg(NO_3)_2$ and with a reminder for the students that water molecules were omitted from the equation to simplify the drawings. This added extra information and the hints provided in the question prompt guided higher percentage of the students to select the correct equation. For this reason, this item was not graphed along with those of other items in the pre-posttest. Nevertheless responses to $CaCl_2$ were instructive in that they revealed new student misconceptions described in a greater detail in the next subsection.

Further analysis and comparison of the immediate pre-posttest data is described in upcoming sections but first I discuss the misconceptions about dissolving ionic compounds revealed by the pre-assessment data.

6.1.2.1. Identification of student misconceptions in the pre-POGIL data

In addition to identifying new misconceptions, the pre-POGIL data confirmed several misconceptions previously reported in the literature (Ebenezer, 2001; Kelly & Jones, 2007, 2008; Kern, Wood, Roehrig, & Nyachwaya, 2010; Naah and Sanger, 2012; Nyachwaya, Mohamed, Roehrig, Wood, Kern, & Schneider, 2011; Smith and Metz, 1996; Smith and Nakhleh, 2011), including the idea that "ionic salts react with water through displacement to form an acid and a metal oxide or hydroxide when dissolved" (Naah & Sanger, 2012, p188). In the Naah and Sanger (2012) study, the misconception that dissolving ionic solids react with water was the most popular response.

Student responses in the pre-POGIL data in this study revealed six major student misconceptions related to what happens to ionic solids placed in water. Table 6.1 lists these misconceptions along with the number and percent of students with each misconception. These included the idea that ionic compounds react with water to form an acid and a metal oxide; ionic solids dissolve into water and form one combined large molecule; ionic solids in water dissociate into charged particles that are covalently bonded to each other; polyatomic ions dissociate into individual segregated ions; ionic solids dissociate in water as neutral atoms or molecules; and confusion of coefficients and subscripts. The misconception that dissolving ionic solids and water morph into a large individual molecule has not been reported previously with respect to ionic compounds. Kern, Wood, Roehrig, and Nyachwaya (2010) previously reported similar finding with respect to molecular compounds. The following paragraphs describe each misconception and its prevalence in a greater detail.

Table 6.1
List of six student misconceptions identified in this study. The number and percent of students with the identified misconceptions is also shown.

Misconceptions Identified	**K_2SO_4**		**$Mg(NO_3)_2$**		**$CaCl_2$**		**Total**
	N	%	*N*	%	*N*	%	%
1. Ionic solids react with water via double displacement reaction	41	55	40	55	—	—	55
2. Ionic solids "dissolve into water" and form one combined large molecule	18	24	15	21	—	—	23
3. Ionic solids in water dissociate into charged particles that are not separated in space	—	—	—	—	15	20	20
4. Ionic solids dissociate in water as neutral atoms or molecules	—	—	—	—	12	16	16
5. Coefficient/subscript related misconceptions	3	4	5	7	—	—	5
6. Polyatomic ions dissociate into individual, segregated ions	1	1	2	3	—	—	2

6.1.2.2. Misconception 1: dissociating ionic compounds react with water

The most popular misconception in this study was the idea that ionic compounds react with water to form an acid and a metal oxide (see Table 6.2). 55% of those responding chose this misconception (41/74 for K_2SO , 40/73 for $Mg(NO_3)_2$), thinking dissolved K_2SO_4 and $Mg(NO_3)_2$ undergo double displacement reactions in which the potassium and the magnesium ions combine with oxygen to form metal oxide and the sulfate and the nitrate ions combine with hydrogen to form an acid (Table 6.2). This option was not available for $CaCl_2$, the third pretest item. For $CaCl_2$, the distractors in the multiple-choice option were particulate drawings with different set of student misconceptions.

Table 6.2
Illustration of Misconception 1 with K_2SO_4 and $Mg(NO_3)_2$ (expected response, shaded in gray, is illustrated with the dissolution of K_2SO_4; only 15% chose the correct response)

Misconception 1 (55%) *Ionic solids react with water via double displacement reaction*	**Symbolic equations showing misconception**
Expected response (15%)	$K_2SO_4\ (s) \rightarrow 2K^+\ (aq) + SO_4^{2-}\ (aq)$
Potassium sulfate, K_2SO_4 (55%)	$K_2SO_4\ (s) + H_2O\ (l) \rightarrow K_2O\ (aq) + H_2SO_4\ (aq)$
Magnesium nitrate, $Mg(NO_3)_2$ (55%)	$Mg(NO_3)_2\ (s) + H_2O\ (l) \rightarrow MgO(aq) + 2HNO_3\ (aq)$

The prevalence of Misconception 1 suggests the students were focusing on the symbolic features present in the chemical equations (i.e. water) and not what the equations represented. This finding is consistent with the findings in chapter 4 where we saw groups focus on water in their initial dialogue as a criterion to guide their selection of which chemical equation represents the dissolution of NaCl. Many groups, as you may recall, justified their selection of option B of the multiple choice options (see Figure 6.2) by reasoning the equation needed to show the addition of water to the salt. The sociochemical dialogue of Group 1C is reproduced here as Figure 6.2 to illustrate this point.

Directions: Based on your particulate diagrams, which of the following balanced equations shows what happens to sodium chloride (NaCl) placed in water?

f. $NaCl\ (s) \rightarrow Na\ (aq) + Cl\ (aq)$
g. $2NaCl\ (s) + H_2O\ (l) \rightarrow 2HCl\ (aq) + Na_2O(aq)$
h. $NaCl\ (s) \rightarrow Na^+(aq) + Cl^-(aq)$
i. $NaCl\ (s) \rightarrow Na^+(s) + Cl_2^-(s)$
j. $NaCl\ (s) \rightarrow Na^+(s) + Cl^-(s)$

Group's Dialogue
188 S1: This should be B because … the fact that it's showing two ions. Plus the H_2O …
189 S2: What are you guys looking at
190 S1: We are on 3
191 S2: Yeah, B makes sense
192 S1: For one thing it's the only one you're adding water to. The other ones aren't adding water to it. They have an equation without water
193 S3: It's definitely not D and E. I don't think it's A or C because they don't have the water in the equation
194 Okay [*group chooses B and moves on to the next activity]*

Figure 6.2. Group 1C's sociochemical dialogue with respect to the dissolution of NaCl.

As shown in the Figure 6.2, Group 1C focused in their discourse entirely on option B of the multiple-choices. Option B contained Misconception 1 – salt reacting with water to form acid and metal oxide. The group's justifications for selecting option B was based what symbolic features were present in the equation. For instance, *S1* justifies the selection of option B on the basis that it is the only equation adding water to the salt – "it's the only one you're adding water to" (*S1*, LN 5). We similarly see the group use water as exclusionary criterion to rule out the other options in the multiple-choice question. For instance, in line 6 of Figure 6.2, *S3* argues "I don't think it's A or C because they don't have the water in the equation." This suggests that the group was concerned with the role of water in the process and selected the equation showing the water reacting with the salt. This appears to be consistent with the prevalence of this same misconception in the students' immediate pre-POGIL data (Misconception 1). Therefore, the concurrence of the findings in this section and chapter 4 suggests the focus on water reflects genuine student misunderstanding on what happens to ionic compounds in aqueous solution.

Further evidence for Misconception 1 came from pretest data administered during the first day of classes (early-pretest data). In the early pretest data, students were asked to describe, in words, what happens when certain ionic solids are placed in water (e.g., KI) and to write a balanced equation that shows what happens to potassium iodide (KI) placed in water. The question was administered as a free-response item. Several students wrote that KI will undergo displacement reaction in which the cations and anions exchange partners. The following are illustrative student responses:

> *"The KI would react with the water. The potassium would bond with the oxygen & hydrogen with iodine. It would be a double replacement reaction." – S33*
>
> *"The compounds perform a double displacement in which both of the cations switch anions. An explosion may also occur." – S29*
>
> *"The KI molecules and the H_2O molecules combine to form a solution of two compounds, hydroxide and potassium hydroxide" – S115*
>
> "*It breaks apart and bonds with water." – S9*
>
> *"The water will breakdown the crystals and the KI will dissolve. It will do this by combining with the elements." – S123*
>
> *"The potassium iodide crystals will dissolve in water. The atoms will start to change spots." – S35*

The student responses indicate their belief that ionic solids react with water via double displacement reaction in which the water breaks down the salts and results formation of new compounds. Table 6.3 shows the actual balanced equations the quoted students above generated for the dissolution of KI (if they provided a response, as some students did not provide any equation). 22% of the student-generated equations showed double displacement reactions in which the cations and anions exchanged partners. Their written equations are thus consistent with their belief that a double displacement reaction occurs.

Table 6.3
Sample student responses and student-generated symbolic equations in response to *"what happens to solid potassium iodide (KI) placed in water?"* in early-pretest.

Student Code	Student-generated Equation
S9	$KI + H_2O \rightarrow KH_2 + OI$
S29	$2KI + H_2O \rightarrow K_2O + 2HI$
S33	$2KI + H_2O \rightarrow K_2O + 2HI$
S35	—
S115	$KI + H_2O \rightarrow HI +$ [crossed out] KHO
S123	$2KI_{(s)} + H_2O_{(aq)} \rightarrow 2KH + IO$

6.1.2.3 Misconception 2: ionic salts dissolve into water and form a new molecule

23% of students responding believed ionic salts dissolve into water, combining with the water to form one large individual molecule (see Table 6.4 below; 24% with respect to K_2SO_4 and 21% with respect to $Mg(NO_3)_2$). In this case, ionic solids and water were shown as discrete compounds in the reactant side of the equation but amalgamated into one bonded mass in the product side (Table 6.4). It is possible the students were drawn to this option because of the water molecules shown in the reactant side of the equation. However, in addition to focusing on the water they were selecting an option with inappropriate groupings of discrete compounds.

Table 6.4
Illustration of Misconception 2 with K_2SO_4 and $Mg(NO_3)_2$ (expected response, shaded in gray, is illustrated with the dissolution of K_2SO_4; only 15% chose the correct response)

Misconception 1 (23%) *Dissolving ionic solids and water morph into a larger individual molecule*	**Symbolic equations showing misconception**
Expected response (15%)	$K_2SO_4\ (s) \rightarrow 2K^+\ (aq) + SO_4^{2-}\ (aq)$
Potassium sulfate, K_2SO_4 (24%)	$K_2SO_4\ (s) + H_2O\ (l) \rightarrow K_2OH_2SO_4\ (aq)$
Magnesium nitrate, $Mg(NO_3)_2$ (21%)	$Mg(NO_3)_2\ (s) + H_2O\ (l) \rightarrow MgOH_2NO_3\ (aq)$

The prevalence of Misconception 2 in the immediate pre-posttest data suggests many students hold completely different understanding of how atoms combine in chemical reactions. Earlier studies by Kern, Wood, Roehrig, & Nyachwaya (2010) noted similar findings with respect to student understanding of molecular compounds. In their study, Kern and colleagues found students represented the products of methane (CH_4) combustion (CO_2 and H_2O) as amalgamated mass of atoms in which CO_2 and H_2O were bonded into one large mass. The authors suggested the combination of unlike species "indicates such representations may have originated from completely different understanding of how atoms and molecules combine in chemical reactions" (Kern, Wood, Roehrig, & Nyachwaya, 2010, p.170). While the students in that study were dealing with a molecular compound, the students in this study seem to use the same thinking to describe ionic compounds in terms of amalgamating discrete atoms, ions, and molecules into one large mass.

Further evidence for Misconception 2 came from the early-pretest data. In their written responses for what happens to solid KI dissolved in water, several students mentioned the salt "dissolving into the water" and combining with it to form one larger molecule. The following quotes represent many such declarations:

"It [KI] dissolves in the water and becomes part of the water molecules. They combine." – S3

"The crystals dissolve in the water, making a new substance." – S31

"The bonds holding atoms of the solid crystal together of KI break and mix with H_2O atoms." – S57

"The solid KI dissolved into the water." – S41

"The solid KI broke down and was physically combined to the water." – S77

"When KI hit the water the molecules disperse rapidly to attach themselves with H_2O to produce a solvent." – S71

These responses suggest the students believe ionic compounds "dissolve into" water and combine with water to form new compounds. Table 6.5 below shows the actual equations the quoted students generated for the KI dissolution. 25.6% of the student-generated equations showed KI and H_2O amalgamated into one large molecule. Their written equations are thus consistent with their belief that KI "dissolved into water" and combined with it through chemical reaction.

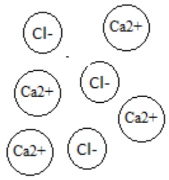
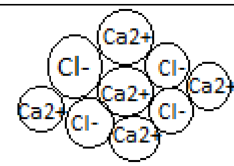
Table 6.5
Sample student responses and student-generated symbolic equations in response to *"what happens to solid potassium iodide (KI) placed in water?"* in early pretest.

Student Code	Student-generated Equation
S3	$KI + H_2O \rightarrow KIH_2O$
S31	$KI + H_2O \rightarrow KIH_2O$
S41	$KI + H_2O \rightarrow KIH_2O$
S57	$KI + H_2O \rightarrow KIH_2O$
S71	H_2OKI
S77	$KI + H_2O \rightarrow KIH_2O$

6.1.2.4 Misconception 3: ionic solids dissociate into charged bonded particles

20% of students responding thought solid $CaCl_2$ placed in water changed into charged particles covalently bonded to each other (Table 6.6). This is in contrast to the accepted chemical the idea that the individual ions of water-soluble ionic solids dissociate from one another and are separated in space (see expected correct response in Table 6.6; course instructor omitted water molecules from the drawings and ignored appropriate sizes).

Table 6.6
Illustration of Misconception 3 (20%) with $CaCl_2$: *Ionic solids in water dissociate into charged bonded particles (water molecules were omitted from the drawings)*

Drawing with correct response (60%)	Drawings showing Misconception 3 (20%)	
	 *Multiple-choice option*	 *Student-generated*

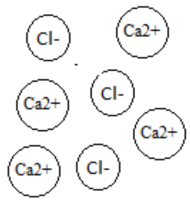
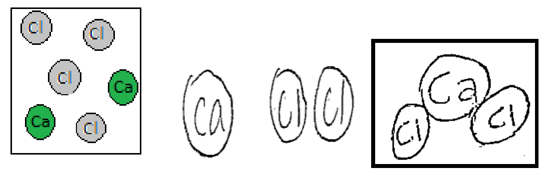
It was not clear from the student responses if the charges on the calcium and chloride drew them to the option showing Misconception 3 or the fact that calcium and chloride ions were shown in a matrix format in which they were next to each other. In the initial pretest, students either drew $CaCl_2$ as a molecular compound or left the response area blank. Thus, unlike Misconception 1 and 2, there were no early-pretest student drawings from the student cohort in this research to provide further strengthening evidence for Misconception 3. Similarly, students were not asked to verbally describe what happens to $CaCl_2$.

In choosing Misconception 3, it is feasible the students understood the particles were charged but lack understanding of what happens to the ionic solids at the particulate level. Thus, with respect to $CaCl_2$, students understand calcium and chloride are charged particles but show the charged particles as touching and covalently bonding (Table 6.6). It was not obvious from the data if the students know or understand that solid $CaCl_2$ contains discrete ionic pairs that are internally ionically bonded.

6.1.2.5 Misconception 4: ionic solids dissociate as neutral atoms and molecules

16% of students responding to the immediate-pretest questions thought solid $CaCl_2$ dissociates into neutral calcium and chloride atoms (see Table 6.7). The students in this case seem to understand ionic solids placed in water dissociate but think the discrete ions in ionic compounds dissociate into neutral atoms and molecules (Table 6.7).

Table 6.7
Illustration of Misconception 4 (16%) with $CaCl_2$

Drawing with correct response (60%)	Drawings showing Misconception 3 (20%)
	
	Multiple-choice option student-generated drawings

Further supporting evidence for this assertion comes from student responses in the early-pretest data. In their written responses with respect to the dissolution of KI, several students wrote KI 'breaks down' or dissociates into individual atoms. The following quotes are illustrative of this common student misconception:

> *"The KI breaks down into potassium and iodine." – S27*
>
> *"The water broke down the potassium iodide crystals and the atoms of KI and H_2O freely mix." – S89*
>
> *"The molecules interact and electrons are shared to make each molecule happy and complete." – S83*
>
> *"The individual molecules of K and I molecules are floating around, suspended in solution." – S113*
>
> *"The KI will disperse into the water until it can no longer spread out." – S163*

Table 6.8 shows the actual symbolic equations generated by the above students to represent the dissolution process of KI. Their drawings are consistent with their belief that dissolving ionic solids dissociate into neutral atoms and molecules.

Table 6.8
Sample student responses and student-generated symbolic equations in response to *"what happens to solid potassium iodide (KI) placed in water?"* in early pretest.

Student Code	Student-generated Equation
S27	$KI + H_2O \rightarrow H_2O + I + K$
S83	$KI + H_2O = K + H_2 + I$

S89	$\_KI + \_H_2O \rightarrow K + I + H_2O$
S113	$KI_{(s)} + H_2O_{(l)} \Rightarrow K_{(aq)} + I_{(aq)} + H_2O_{(aq)}$
S151	$KI + H_2O \rightarrow H_2 + O + K + I$
S163	$KI + H_2O \rightarrow KO + H_2 + I$

6.1.2.6 Misconception 5 and 6: polyatomic dissociation and coefficient/subscript errors

Misconceptions 5 and 6 were the least prevalent among the six misconceptions identified in the study. Table 6.9 below shows variations of the symbolic equations showing both Misconception 5 and 6 with respect to K_2SO_4 and $Mg(NO_3)_2$. In Misconception 5, 4% and 7% of the students confused subscripts in symbolic equations representing K_2SO_4 and $Mg(NO_3)_2$ with their coefficients, respectively. In Misconception 6, 1% and 3% of the student thought polyatomic ions dissociate into segregated individual ions such that the sulfate ion (SO_4^{2-}) dissociates into S^{2-} and $4O^{2-}$. Because the early-pretest assessment did not directly ask students to explain their thinking with respect to equations containing polyatomic ions, no further supporting data was available for these misconceptions.

Table 6.9
Samples of Misconceptions 5 and 6

	Symbolic equation showing Misconception
Misconception 5 (5%)	
K_2SO_4	$K_2SO_4\textit{(s)} \rightarrow (K^+)_2\textit{(aq)} + SO_4^{2-}\textit{(aq)}$
$Mg(NO_3)_2$	$Mg(NO_3)_2\textit{(s)} \rightarrow Mg^{+2}\textit{(aq)} + (NO_3^-)_2\textit{(aq)}$
Misconception 6 (2%)	
K_2SO_4	$K_2SO_4\textit{(s)} \rightarrow 2K^+\textit{(aq)} + S^{2-}\textit{(aq)} + 4O^{2-}\textit{(aq)}$
$Mg(NO_3)_2$	$K_2SO_4\textit{(s)} \rightarrow Mg^{+2}\textit{(aq)} + 2N^{3-}\textit{(aq)} + 6O^{2-}\textit{(aq)}$

6.1.2.7 Section summary

Sections 6.1.1 and 6.1.2 provided class-level analysis with respect to symbolic level data mainly consisting of pre-posttest data. The analysis revealed the class as a whole performed poorly on measures of pretest assessment, based on the percentage of students who selected correct equation for dissolving ionic compounds (Figure 6.1). It is worth noting here that the students had been taught about ionic bonding and had a year of high school chemistry, thus the occurrence of these misconceptions is alarming given the amount of instruction students received. Students did appear to do much better post-POGIL (Figure 6.1). The more interesting data came from analysis of student misconceptions (Section 6.1.2). The pre-POGIL assessment data revealed six different student misconceptions with respect to what happens to ionic compounds placed in water (Table 6.1). These included the idea that ionic compounds react with water to form an acid and a metal oxide; dissolving ionic solids and water morph into a larger individual molecule; ionic solids in water dissociate into charged particles that are covalently bonded to each other; polyatomic ions dissociate into individual segregated ions; ionic solids dissociate in water as neutral atoms or molecules; and confusion of coefficients and subscripts. Prevalence of these misconceptions ranged from 3% to 26%.

The results in Sections 6.1.1 and 6.1.2 established that the student in this study had poor understanding of what happens to dissolved ionic compounds and held wide range of misconceptions related to the nature of aqueous ionic compounds. The following section examines the impact of the POGIL activities on students' conceptions of ionic compounds in solution by comparing the pre- and post-POGIL data.

6.1.3. Analysis of pre-post POGIL data

To assess the impact of the POGIL activities on student misconceptions and overall conceptions of ionic compounds, I compared the pre-POGIL data with post-POGIL data, similar to the analysis I briefly conducted in chapter 4 with respect to the discussion of shifts in student thinking. In the immediate pre-posttest questions, students received a score of one point if they selected the correct response and a score of zero if they selected the incorrect response. Because there were three questions in each test related to ionic solids, individual students had the potential to earn up to a maximum of three points in each test. I carried out matched immediate pre-posttest analysis based on the percentage of correct responses students earned as they answered the immediate pre-posttest questions. Table 6.10 shows the results. Although there was a total of 74 students who participated in the POGIL activities, 8% did not complete either the pretest or the posttest. Thus actual analysis was based on a matched sample of 68 students. In addition to the descriptive statistics shown in Table 6.10, statistical significance for the matched immediate pre-posttest samples was analyzed by using paired *t*-test statistic.

Table 6.10
Comparison of whole-class immediate pre-post POGIL performance based on selection of correct symbolic equations representing what happens to ionic solids in water (mean scores reflect the average % correct for each item – matched sample was used for analysis).

`	**Pretest** ***Mean ± SD (%)***	**Posttest** ***Mean ± SD (%)***	***t*-test (*deg. freedom*)**	**Effect Size**
Average % correct	30.8 ± 31.2	84.9 ± 21.1	11.85 (117.6)*	2.03
Question 1	16.2 ± 37.1	89.6 ± 30.8	33.14 (67.04)*	2.15
Question 2	16.2 ± 37.1	89.7 ± 30.6	33.14 (67.04)*	2.16
Question 3	60.3 ± 49.3	80.0 ± 40.3	32.96 (67.07)*	0.44

**These items were statistically significant at p < 0.001*

As shown in Table 6.10, in general, students participating in this study scored significantly better in the post-POGIL test ($t(118) = 11.85$, $p < 0.001$). The computed effect size indicates the average score on the immediate posttest was more than 2.03 standard deviations greater than the average score on the immediate pretest (effect size = 2.03, Table 6.10). These statistical results show that after experiencing the POGIL activities the majority of students in this study improved their understanding of what happens to ionic solids placed in water (% average correct score of 30.8 vs. 84.9 for pre- vs. posttest, $p < 0.001$, Table 6.10).

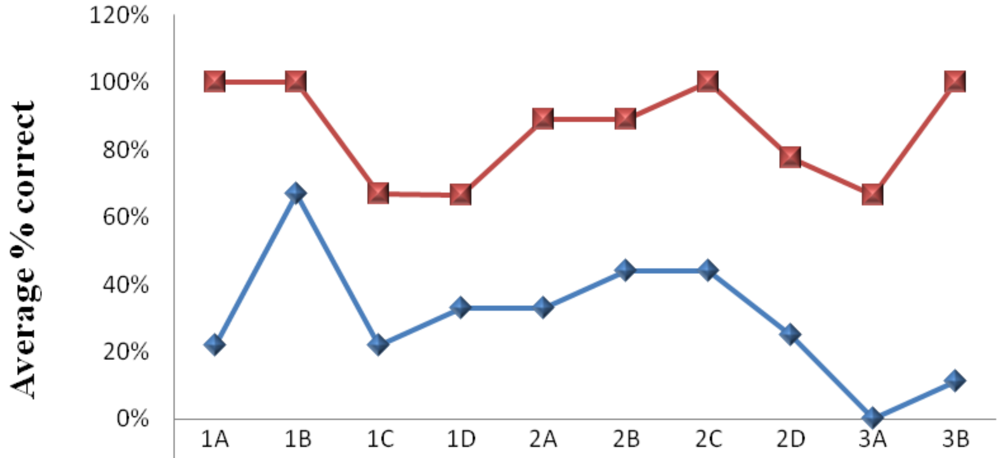
The improvement in student understanding of ionic compounds in solution post-POGIL was coupled to reduction in the frequency of the misconceptions identified in the previous section (section 6.1.2). Table 6.11 compares the previous data showing the pre-POGIL data with the post-POGIL results. In the immediate pre-test data, 55% of those responding believed Misconception 1, the most popular misconception. In the post-POGIL activity, only 2% of the students now believed dissolving ionic solids react with water to form a metal oxide and an acid. This is consistent with the shift towards higher percentage of the students selecting the correct response as supposed to Misconception 1. Similarly, the percentage of students who believed Misconception 2 fell from a high of 23% pre-POGIL to a low of 1% post-POGIL (Table 6.11). These two misconceptions (Misconception 1 and 2) were the top responses for most students in the immediate pretest data but now accounted for less than 3% together.

Table 6.11
Use of POGIL activities reduced dramatically major misconceptions identified in this study (post-POGIL findings are shaded gray)

Nature of Misconceptions	Prevalence of Misconception	
	Pretest (%)	Posttest (%)
Misconception *Ionic solids react with water via double displacement reaction*	55	2
Misconception 2 *Dissolving ionic solids and water morph into a larger individual molecule*	22	1
Misconception 3 *Ionic solids in water dissociate into charged bonded particles*	20	—
Misconception 4 *Ionic solids dissociate in water as neutral atoms or molecules*	16	3
Misconception 5 *Coefficient/subscript related misconceptions*	5	6
Misconception 6 *Polyatomic ions dissociate into individual, segregated ions*	2	4

6.1.3. Group-level analysis

Given the overall impact of the POGIL activities at the class-level, I examined closely how the activities impacted the ten different groups that were the focus of this study. I carried out the analysis in a manner similar to the previous section for the whole-class analysis. That is, individual students received a score of one point if they selected the correct response and a score of zero if they selected the incorrect response in the immediate pre-posttest questions. Figure 6.3 compares the groups' pre-post POGIL performance and the average percent correct (%) earned by the 10 groups in the study.



	1A	1B	1C	1D	2A	2B	2C	2D	3A	3B
Pretest	22%	67%	22%	33%	33%	44%	44%	25%	0%	11%
Posttest	100%	100%	67%	67%	89%	89%	100%	78%	67%	100%

Figure 6.3: Matched immediate pre-posttest data for the 10 groups in the study. Blue lines represent the pretest data and red lines the posttest data. Groups significantly scored better on the posttest.

As can be seen in Figure 6.3, the evidence suggests the groups on average did better in choosing the correct response for dissolving ionic solids post-POGIL. The groups' average immediate pre-POGIL percent correct score was 29.3 ± 27 and their average post-POGIL score 85.6 ± 19.5 (Table 6.12). The percent correct scores in Table 6.12 reflect the average scores for all groups excluding Group 1B and 3A. These two groups (1B and 3A) had outlier average scores of 67% and 0% in the pre-test data respectively. As such, their scores were excluded from the final data analysis. The groups' percent average correct in the pretest was comparable to the class average percent score (M = 29.3 vs. M = 31 for groups vs. whole-class) as were the posttest scores (M = 85.6 vs. M = 84 for groups vs. whole-class). Thus, the impact of the POGIL activities on groups was reflective of the class's performance.

Table 6. 12
Comparison of group immediate pre-posttest % correct for symbolic equations representing what happens to ionic solids in water (data is sorted by posttest % mean)

Group	Pretest[1] *Mean ± SD* (%Correct)	Posttest[1] *Mean ± SD* (%Correct)	*t*-test (*deg. freedom*)	*p*-Value	Effect Size
Average[2]	29.3± 27	85.6 ± 19.5	8.381 (45)	0.000	2.28
1C	22 ± 19	67 ± 0.0	4.091 (2)	0.050	3.35
1D	33 ± 27	67 ± 27	1.732 (6)	0.134	1.26
3A[2]	—	—	—	—	—
2D	25 ± 16	78 ± 19	3.873 (4)	0.012	3.02
2A	33 ± 0.0	89 ± 19	5.091 (2)	0.036	4.17
2B	44 ± 51	89 ± 19	4.673 (4)	0.009	1.17
1A	22 ± 19	100 ± 0.0	7.091 (2)	0.012	5.81
1B[2]	—	—	—	—	—
2C	44 ± 51	100 ± 0.0	1.892 (2)	0.199	1.55
3B	11 ± 19	100 ± 0.0	8.091 (2)	0.0149	6.62

[1]*There were 33 students in the 10 groups. 9% of the students did not complete either the pretest or the posttest data, thus final analysis was based on 30 out of the 33 students whose scores were matched.*
[2]*This number reflects the average % correct for all groups excluding Group 1B and 3A. These two groups had outlier average scores of 67% and 0% in the pre-test data, respectively. Their results were thus excluded from the data analysis. As such, the average score is for the remaining 8 groups.*

With respect to the groups, the numerical evidence suggests that, in general, the ten groups in the study scored significantly better in the post-POGIL test ($t(45) = 8.381$, $p = 0.000$, Table 6.12). The effect size indicates the average score on their immediate posttest was more than 2.28 standard deviations greater than the groups' average score on their immediate pretest (effect size = 2.28, Table 6.12). These statistical results show that after experiencing the POGIL activities the majority of groups in the study improved their understanding of what happens to ionic solids placed in water. The exceptions were Groups 1D and 2C whose pre-posttest scores were not statistically significant ($p > 0.01$). However, the computed effect size for these two groups was greater than 1, suggesting their average scores on the posttest was at least one standard deviation better than their pretest scores.

Across group comparisons revealed there were three types of performances in the groups' post-POGIL performance: high, medium, and low performers. Groups in the high performance category (1A, 2C, and 3B) earned all possible points in the post-POGIL test. For these groups, their percent correct on the post-POGIL test was 100% (Table 6.12). Those in the medium category (Groups 2A, 2B, and 2D) had percent correct scores between 78% and 89% (Table 6.12). Groups in the low-performance category (1C and 1D) had an average percent correct of 67%. Group 1C was one of two groups in the study that focused on water as their sole criteria to guide their selection of the correct multiple choice equation for dissolved ionic solids during their sociochemical dialogues in chapter 4 (see section 4.1.2). The group did not discuss ions or aqueous as criteria and their limited understanding of how ionic solids behave in water is reflected on their post-POGIL performance. Members of Group 1D, on the other hand, had extensive discourse on option B versus option C in chapter 4 and similarly were involved in extensive teacher-initiated dialogical discourse about what counts as acceptable particulate representation of dissolved ionic solids (see Chapter 5). Thus while all groups performed better on the post-POGIL tests, such performance varied within the groups, with the nature of their sociochemical dialogues predicting to a certain degree their performance on achievement measures (tests, etc.).

The overall evidence suggests the POGIL activities had a positive impact on the groups' understanding of the nature of ionic compounds in solution. For most groups their post-POGIL scores were significantly better than their pre-POGIL score. The groups' performances similarly mirrored the whole-class findings discussed in the previous section. The totality of this evidence, therefore, supports the assertion that POGIL activities impacted group performances.

6.1.4. Section summary

Findings in Section 6.1 established the impact of the POGIL activities on student conceptions of ionic compounds placed in water. Following the POGIL activities, students' understandings of the dissolving process were generally improved, a claim based on the observation that the percentage of students who were selecting the correction multiple choice option of symbolic equations representing dissolution process was generally higher in post-POGIL vs. pre-POGIL. Similarly, data in this section revealed six different student misconceptions about the dissolving process. These included the idea that ionic compounds react with water to form an acid and a metal oxide; dissolving ionic solids and water morph into a larger individual molecule; ionic solids in water dissociate into charged particles that are covalently bonded to each other; polyatomic ions dissociate into individual segregated ions; ionic solids dissociate in water as neutral atoms or molecules; and confusion of coefficients and subscripts. Prevalence of these misconceptions amongst students in the pretests ranged from a low of 3% to a high of 26%. Analysis of pre-post-POGIL measures of student achievement strongly suggested the POGIL activities improved student conceptions of the dissolution of ionic solids in water, with the highest recorded percentage for a misconception being 6% in the post-POGIL data vs. a high of 26% in the pre-POGIL data. However, analyses were mainly driven by symbolic-level data that may not be indicative of students' understanding of what is happening at the particulate level. The next section (6.2) provides this analysis.

6.2. Analysis of particulate-level data

As stated above, the data in the previous section looked at student responses based on symbolic level data. Students were similarly asked to imagine seeing the atoms, molecules, and ions present in dissolving ionic compounds and generate particulate drawings depicting what they might see at the atomic/molecular level, in the hopes of capturing their conceptual understanding of the dissolution process. The following examines what the students' particulate drawings revealed about their particulate level understanding. This analysis was done at the class-level, with qualitative analysis being discussed in section 6.2.1 and quantitative analysis in section 6.2.2.

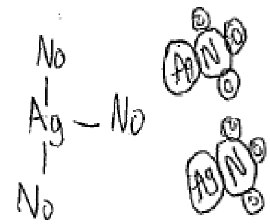
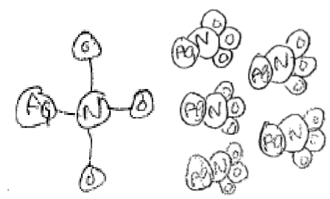
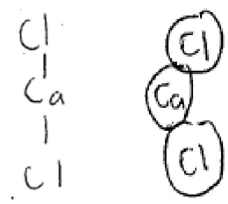
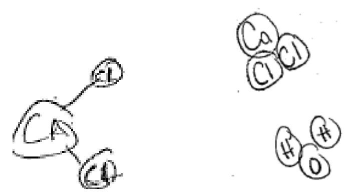
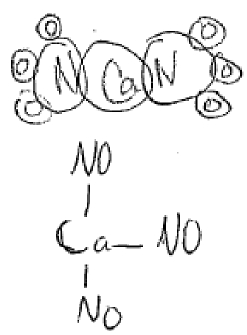
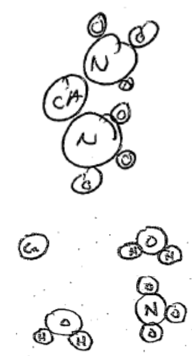
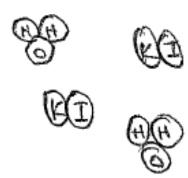
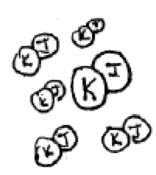
6.2.1. Qualitative analysis of students' particulate-level understanding of the dissolving of ionic compounds in water

There were a total of 177 pre-POGIL student drawings dealing with four ionic compounds [$CaCl_2$*(aq)*, $AgNO_3$*(aq)*, $Ca(NO_3)_2$*(aq)*, and KCl*(aq)*] and 158 post-POGIL drawings dealing with two ionic compounds [$CaCl_2$*(aq)* and $CaCO_3$*(aq)*]. The differences in the number of pre-post POGIL particulate drawings were accounted for by differential student responses in the pre-POGIL test vs. post-POGIL: response rate was much higher post-POGIL, with only 1.3% blank answers versus 41.7% in the pre-POGIL test. Drawings were grouped into one of four major themes based on the framework the students used to represent the ionic solids at the particulate level: i) a molecular framework with discrete atoms and molecules, ii) an ionic framework with discrete ions separated in terms of space, iii) a quasi-ionic framework in which drawings showed partial ionic-partial molecular thinking, and iv) an all-encompassing "Other" category. The following paragraphs describe each theme and the frequency in which it occurred in a greater detail, excluding blank responses.

6.2.1.2. Molecular framework with discrete atoms and molecules

71.2% of the students' pre-POGIL representations depicted dissolved ionic compounds as molecular entities in which discrete ionic species were shown as though covalently bonded through electron sharing. Table 6.13 shows sample pre-post POGIL drawings from multiple students (drawings in a row are from different students) to illustrating this theme. For instance, for $CaCl_2$ and $AgNO_3$, students used touching circles and lines (Cl—Ca—Cl and Ag–NO_3) to represent these compounds. Similar to our earlier work with molecular compounds (Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011), errors such as attentiveness to conservation of matter were ignored when determining the appropriateness of the representations. Following the POGIL intervention, 24.1% of the student drawings still depicted dissolved ionic compounds as molecular (Table 6.13). Again, even after the POGIL intervention, these representations still showed dissolved ionic compounds as molecular entities with discrete atoms covalently attached to each other in discrete molecules. The pre-post-POGIL drawings in Table 6.13 illustrate the similarity of student responses when using this alternative framework to depict dissolved ionic solids at the particulate level.

Table 6.13
Sample responses showing the molecular framework theme in pre-post-POGIL tasks

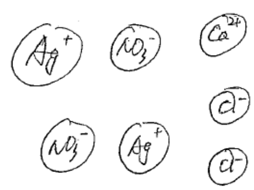
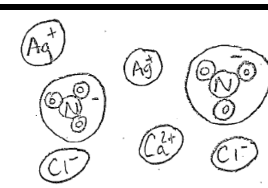
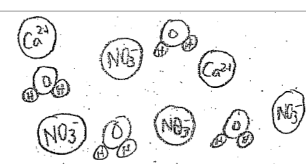
Compound(s)	Pre-POGIL drawings *(frequency: 71.2%)*	Post-POGIL drawing *(frequency: 24.1%)*
Samples of $AgNO_3$*(aq)*		
Samples of $CaCl_2$*(aq)*		
Sample of $Ca(NO_3)_2$*(aq)*		
Samples of KI *(aq)*		—
		—

The persistency of molecular drawings to depict dissolution of ionic solids in water, and students' inability to distinguish between ionic and covalent bonds, suggests many have different conception of how chemical bonds form. Such finding is consistent with Taber's (1998) use of "alternative molecular framework" to describe how students view the ionic bond – many focus on electron transfer events between neutral atoms which leads them to assume there must be a bond shared between cations such as Ca^{2+} and anions such as Cl^{-} and hence the covalent bond within the $CaCl_2$ compound.

6.2.1.3. Ionic framework with discrete ions separated in space

2.3% of students' pre-POGIL drawings and 43% of their post-POGIL drawings were coded as using ionic framework showing appropriate particulate representation (see Table 6.14). Representations in this category showed ionic compounds dissolved in water as discrete charged ionic species separated in space and sometimes randomly distributed. Such depictions are consistent with accepted scientific models of what happens to dissolved ionic compounds at the particulate level.

Table 6.14
Sample responses showing the use of ionic framework in pre- and post-POGIL activities

Themes	Pre-POGIL drawing	Post-POGIL drawing
Sample of $CaCl_2$*(aq)* and $AgNO_3$*(aq)*		
Sample of $Ca(NO_3)_2$*(aq)*	–	

6.2.1.4. Quasi-ionic framework

Representations in this category showed aqueous ionic compounds as discrete charged species but not randomly distributed or separated in space or charged but still encapsulated in touching circles as if covalently bonded though charged (see Table 6.15

for sample student responses). None of the drawings in the pre-POGIL activities depicted dissolved ionic solids this way while 16.5% of the post-POGIL drawings fit into this category. The Quasi-ionic representations show partial understanding of what happens to dissolving ionic compounds but not a full grasp of the dissolving process. Taken together, ionic and quasi-ion drawings accounted for 59.5% of the post-POGIL drawings, indicating full or partial understanding of the nature of ionic compounds dissolved in water.

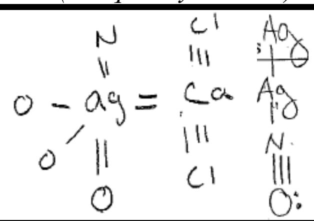
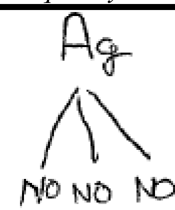
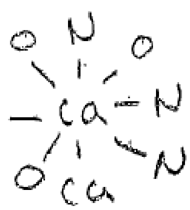
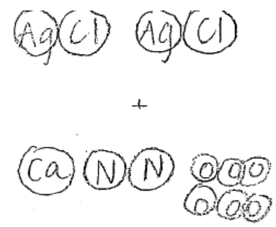
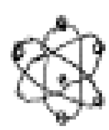
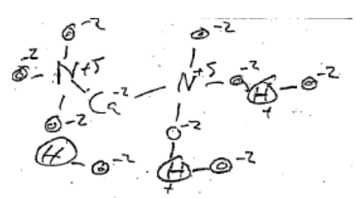
Table 6.15
Sample responses showing the use of quasi-ionic framework in post-POGIL activities (quasi-ionic drawings were not observed in pre-POGIL activities)

Themes	Post-POGIL drawing
Quasi-ionic framework Sample of $CaCl_2$*(aq)* and $AgNO_3$*(aq)*	

6.2.1.5. All encompassing "Other" category

26.6% of the pre-POGIL drawings and 16.5 % of post-POGIL drawings showed other inappropriate representations of dissolved ionic compounds. Representations in this category did not show discrete molecular or ionic compounds but rather incorrect connections between atoms, or inappropriate flocking of atoms, molecules, and compounds into individual bonded mass. For instance, one of the samples shown in Table 6.16 to illustrate this category shows $AgNO_3$ and $CaCl_2$ all connected as individual molecule, with triple bonds between Ca and Cl (Ca-≡-Cl) and double bond between silver and Ca (Ag=Ca). Another shows a flower-like structure of $Ca(NO_3)_2$. Such structures did not fit into either the molecular framework or the ionic framework. Other representations in this category included irrelevant representational attempts or non-particulate representations of ionic compounds. Thus, this category is an all-encompassing category for all diagrams that did not fit either the molecular framework or the ionic framework. Table 6.16 shows sample student pre- and post-drawings depicting this theme.

Table 6.16
Sample responses showing the "other category" framework in pre- and post-POGIL activities

Compound(s)	pre-POGIL drawing *(Frequency: 26.6%)*	Post-POGIL drawing *(Frequency: 16.5%)*
$CaCl_2$*(aq)* and $AgNO_3$*(aq)*		
KI*(aq)* and $Ca(NO_3)_2$*(aq)*		
	 KI + H_2O	

6.2.1.6. Summary

Table 6.17 provides a summary of the categorization of the student drawings in this study. Analysis of these drawings indicated majority of students used molecular framework to depict dissolving ionic compounds at the particulate-level – only 2.3% of the drawings showed appropriate ionic framework while close to 71% were coded as being molecular. In addition to using molecular and ionic frameworks to depict ionic compounds, several drawings were categorized as “other” because they showed inappropriate connections between the atoms or amalgamates of discrete atoms, ions, and molecules as one bonded mass. The frequencies of molecular drawings and other category decreased in the post-POGIL drawings while the frequencies of appropriate drawings for dissolved ionic compounds or those drawings partial understandings increased. However, the question remains *are the observed differences in the proportion of pre- and post-POGIL ionic and molecular drawings significant*? The next section provides quantitative analysis to answer this question.

Table 6.17
Summary of student representations of dissolved ionic compounds in pre-post POGIL

Main Theme	Frequency of framework use (%)	
	Pre-POGIL Drawings	Post-POGIL Drawings
Molecular framework	71.2	24.1
Ionic framework	2.30	43.0
Quasi-ionic	—	16.5
Other	26.6	16.5

6.2.2. Quantitative Analysis of students’ particulate-level understandings

Using the categories developed above (see Table 6.17), I next examined the impact of the POGIL activities on student understanding of the dissolution process quantitatively. Figure 6.4 shows pre-post analysis of how many drawings were shown as molecular in the pre-POGIL activities and how many were shown as molecular post-POGIL. The figure also shows the number of drawings coded as ionic and quasi-ionic in the pre-POGIL and in the post-POGIL activities. The post-test percentiles are markedly better but can we, to restate the question asked above, attribute the observed change in the frequencies to the POGIL activities?

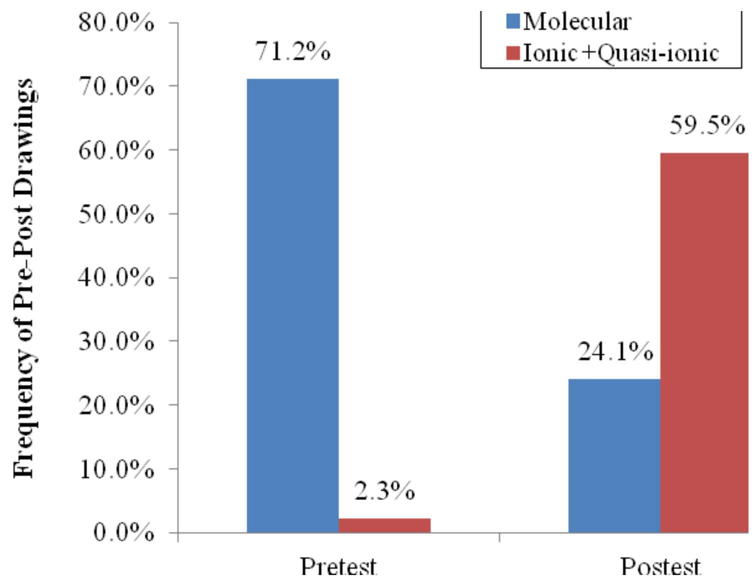


Figure 6.4. Comparison of pre-post POGIL drawings. In the figure, blue colors show the number of pre-post POGIL drawings using molecular framework; red colors shows the number of pre-post POGIL drawings using ionic and quasi-ionic framework. Differences between the pre-post POGIL were statistically significant at p < 0.001 level.

Statistical analysis suggest there was a significant increase in the use of ionic and quasi-ionic frameworks from pre-POGIL to post-POGIL (2.3% vs. 59.5%, $\chi^2(1) = 129.16$, $p < 0.001$). If we consider only drawings that used ionic framework, thereby ignoring those indicating partial thinking through the use of quasi-ionic framework, there is still a significant difference between the use of ionic framework to represent the dissolved ionic compounds in the pre-POGIL activity versus post-POGIL activity (2.3% vs. 43.0%, $\chi^2(1) = 79.55$, $p < 0.001$). In both cases, there was significant evidence to suggest the POGIL activities improved student conceptions of the dissolution of ionic compounds in water.

The increase in the number of student drawings showing appropriate particulate representations of dissolved ionic or partial understanding through the use of quasi-ionic framework were coupled to concomitant reduction in the number of drawings showing ionic compounds as molecular entities in the pre-POGIL vs. post-POGIL (71.2% vs. 24.1%, $\chi^2(1) = 72.23$, $p < 0.001$). These findings suggest that the POGIL activities had a significant impact on student conceptions of ionic compounds at the particulate level. What was not clear from this analysis was if the students retained what they learned during the activities few weeks after completing the activities and whether the students could apply what they learned in new context. The next section (Section 6.3) addresses these questions.

6.3. Measures of Retention and Transferability for whole class and groups

Posttest questions were embedded in the midterm and final exams of the course, administered 2 and 8 weeks after the POGIL activities were completed, respectively. Therefore the midterm and the final exam served as a measure to assess whether the students retained what they learned after moving on to new chemistry topics and whether they could apply the newly learned concepts under new context (transfer their learning to new situations). These two questions are addressed under separate headings as follows.

6.3.1 Retention as measured by symbolic-level data

Figure 6.5 shows the classes' average % correct scores for dissolving ionic compounds represented at the symbolic level at different points in the semester as well as % correct scores from the ten different groups in this study.

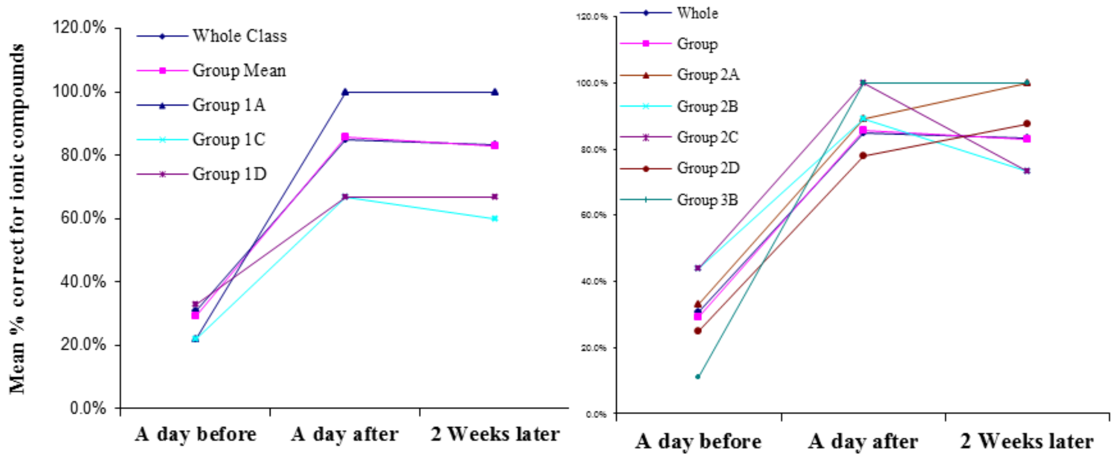


Figure 6.5. Students' retention of concepts learned post-POGIL. The figure shows the students' average percent correct responses for dissolving ionic compounds in water a day before and after the completing the data and 2 weeks after the POGIL activities. (Note: a question about the nature of dissolving ionic solids was asked in week 8 but in an open-ended format as compared to the multiple choice format of the data shown here, excluding the possibility of comparative analysis).

As shown in Figure 6.5, there was a dramatic improvement in the students' representations of dissolved ionic compounds at the symbolic level a day after completing the activity (average % correct score of 84.9% post-POGIL vs. average 30.8% before POGIL for the whole class; average % correct of 85.6% post-POGIL for the ten groups versus 29.4% before POGIL). There was no decay effect observed two weeks after completing the POGIL activities, with average percent correct of 84.9% a day after vs. 83.4% two weeks later for the whole class. The results from the groups were similarly comparable (and average percent correct of 85.6% the day after completing the activities vs. average percent correct of 82.8% after two weeks). Only two groups, Group 2B (89.0% a day after vs. 73.3% two weeks later) and Group 2C (100% a day after vs. 73.3% two weeks later), appeared to have showed slide decay in their concept knowledge (Figure 6.5). Group 2C was the only group out of the ten groups in this study that did not develop any criteria to guide their selection of which multiple choice equation to represent dissolving ionic solids during their sociochemical dialogues described in chapter 4 (see section 4.12). The group's lack of criteria development would have predicted poor performance in future assessments and this data seems to support this observation. Group 2B, on the other hand, developed during their sociochemical dialogues in chapter 4 the idea that ionic solids dissociate into ions and become aqueous to guide their selection yet seem to have lost some of what they have learned according to the data presented here. For the rest of the groups, their % correct score two weeks after the activity was completed was comparable to their % score determined a day after completing eth activity. This suggests that the groups generally retained their newly learned conceptions of what happens to ionic compounds dissolved in water well into the semester.

6.3.2 Concept transferability as measured by particulate-level data

In addition to measuring through the delayed posttests whether students retained concepts learned during the POGIL activities, two items in the delayed post-POGIL assessment allowed comparison of whether students could transfer their understanding of dissolving ionic solids to different contexts. In the midterm exam, students were asked to draw particulate-level diagrams showing what happens to solid calcium nitrate ($Ca(NO_3)_2$) dissolved in water. The question explicitly stated the salt was dissolved in water. On the final exam, administered 8 weeks after the POGIL activities, students were similarly asked to generate particulate diagrams but the question was under different context. Instead of asking the students to draw particulate diagrams showing what happens to salts dissolved in water, the question on the final exam asked the students to generate particulate diagrams for the reaction between aqueous HCl and solid $CaCO_3$ to form aqueous $CaCl_2$ and liquid H_2O plus CO_2 gas. This allows direct comparison of whether students can transfer their understanding of what happens to ionic salts dissolved in water generate particulate drawings of salts resulting from precipitation reactions.

Figure 6.6 shows the percentage of particulate drawings that depicted $Ca(NO_3)_2$ dissolved in water as ionic or quasi-ionic species (see the discussion about the use of ionic framework use to represent ionic compounds in section 6.2.1.3) versus those that depicted the aqueous $CaCl_2$ resulting from the reaction of aqueous HCl and solid $CaCO_3$ as ionic or quasi-ionic. As can be seen in Figure 6.6, the percentage of particulate drawings showing $Ca(NO_3)_2$ as ionic or quasi-ionic framework (59.5%) when students were asked to generate drawing showing its dissolution in water was much higher than particulate drawings of aqueous $CaCl_2$ resulting from the reacting chemicals (38.0%). The difference of 21.5% suggests most students had difficulty transferring their improved understanding of what happens to dissolved ionic compounds into different contexts and/or when different language was used.

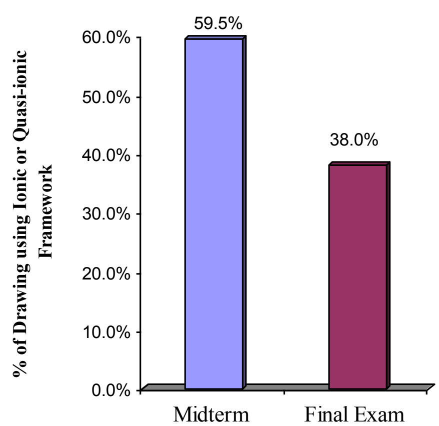


Figure 6.6. Students' use of ionic framework to represent aqueous ionic salts under different contexts (midterm exam asked students to generate particulate drawings of salts mixed in water, final exam question asked about drawings of aqueous salts resulting from precipitation reactions).

This above finding is not surprising. For instance, Kelly and Jones (2008) examined the effects viewing particulate animations of NaCl dissolved in water had students' abilities to transfer their understanding to precipitate reactions between silver chloride (NaCl) and silver nitrate ($AgNO_3$). Similar to our finding here, Kelly and Jones (2008) reported students had trouble transferring their improved conceptions from the particulate animations to the precipitation reaction one week later. Naah and Sanger (2013) similarly reported students having difficulty transferring concepts between animations and static diagrams.

6.4. Chapter Summary

This chapter examined the question of ***how cooperative inquiry-based pedagogies, namely POGIL pedagogy, impact student understanding of the nature of ionic compounds in solution?*** The results analyzed in this chapter revealed the class as a whole performed poorly on measures of pretest assessment but did improve their conceptions of ionic compounds in solution post-POGIL. The data similarly revealed that the student cohorts in this study held wide range of misconceptions related to the nature of aqueous ionic compounds including the idea that ionic compounds react with water to form an acid and a metal oxide; dissolving ionic solids and water morph into a larger individual molecule; ionic solids in water dissociate into charged particles that are covalently bonded to each other; polyatomic ions dissociate into individual segregated ions; ionic solids dissociate in water as neutral atoms or molecules; and confusion of coefficients and subscripts. Prevalence of these misconceptions ranged from a low of 3% to a high of 26%. Post-POGIL, however, there appeared to be erosion of these misconception, with the highest recorded percentage for a misconception being 6% in the post-POGIL data vs. a high of 26% in the pre-POGIL data.

Analysis of students' particulate drawings indicated majority of students used molecular framework to depict dissolving ionic compounds at the particulate-level – only 2.3% of the drawings showed appropriate ionic framework while close to 71% were coded as being molecular in the pre-POGIL tasks. In addition to using molecular and ionic frameworks to depict ionic compounds, several drawings were categorized as "other" because they showed inappropriate connections between the atoms or amalgamates of discrete atoms, ions, and molecules as one bonded mass. The frequencies of molecular drawings and other category decreased in the post-POGIL drawings while the frequencies of appropriate drawings for dissolved ionic compounds or those drawings partial understandings increased dramatically.

One disconcerting finding in the data was students' inability to transfer their newly improved understanding of what happens to dissolved ionic compound when the questions were asked under different context – precipitations reactions versus direct questions asking to show what happens to ionic salts dissolved in water. However, this appears to be a larger question of knowledge transfer and what inhibits that transfer, something that is outside the purview of the current research.

CHAPTER 7

Discussion and Implications

"The solid KI [salt] breaks down and dissolves into water"
Student response, pre-assessment test on ionic compound drawing task

"[What did you struggle with] … the words balanced chemical equation, along with atoms, molecules, and ions, simply because I don't know what they are in chemistry!"
Student response, pre-assessment test on ionic compound drawing task

The aim of this study was twofold. The first goal was to understand how classroom discourse and social interactions influence how individual students in cooperative learning groups understand the nature of dissolving ionic solids in water. A second goal of the study was to examine how targeted instruction, specifically the use of POGIL materials, elicits and corrects commonly held student misconceptions about dissolving ionic solids in water. The emphasis in the latter was to evaluate how interventions that target student misconceptions about ionic compounds affect students' representational fluency and conceptual growth. The guiding research questions, two of which were predesigned and one of which arose organically during the data collection phase, were:

1. How does group thinking during a cooperative inquiry-based activity on chemical bonding influence college students' conceptions of ionic compounds in solution**?**
2. How do teacher's practical moves influence students' meaning making processes and sociochemical norms?
3. How do cooperative inquiry-based pedagogies, namely POGIL pedagogy, impact student understanding of the nature of ionic compounds in solution?

In the following sections, I will summarize findings with respect to each question. Where necessary, results from the different research questions will be combined to triangulate the findings and provide a holistic response to the research question. Following the discussion of the results, I will touch upon the study's implications for research and teaching and future research directions.

7.1. Research question 1: the influences of group thinking on individual learning

Previous studies have documented the benefits of cooperative learning in chemistry (Bowen, 2000; Lewis & Lewis, 2005; Paulson, 1999) and their ability to provide opportunities for classroom discourse in which students collaboratively develop understandings of core chemical ideas (Becker, Rasmussen, Sweeney, Wawro, Towns & Cole 2012; Osborne, 2010; Paulson, 1999). This study, therefore, sought to examine how classroom discourse and established normative aspects of the classroom influenced individual student's understandings of ionic compounds in solution – the first research question. To determine whether ideas became normative and influenced student learning, the following criteria and analytical codes were used (for further description of how the codes were developed, see Chapter 3):

- *Code GNC (Group Negotiated Criteria).* This code was used when there were indications of the student groups negotiating and developing criteria for what counts as an acceptable justification for a chemical phenomenon (e.g., the dissolution of ionic compounds).
- *Code AGC (Across Group-Negotiated Criteria).* This code was used when one or both of the following criteria were satisfied:
    a. Different autonomous groups developed and used similar criteria to explain the same chemical phenomenon.
    b. Different groups used the same criterion as justification for different topics.
- *Code SST (Shifts in Student Thinking).* This code indicated there was a shift in individual student thinking brought about by opposing viewpoints or new information contradicting initial position(s) the students held.

7.1.1. The development of group-negotiated criteria – Patterns within groups

In response to the question of whether were there indications of the student groups negotiating and developing criteria for what counts as an acceptable justification for a chemical phenomenon, I described how individual groups repeatedly used the idea of ionic solids in water separating into ions and becoming aqueous as a justification and guide to select appropriate symbolic equations representing the dissolution of ionic solids in water. There was also appeal to the idea of ionic compounds not transforming chemically upon dissolving. The recurrent use of these chemical ideas (ions, aqueous, chemical change) provided evidence for the presence of sociochemical norms, a normative type of reasoning based on chemical justifications evident in group discourses and repeatedly by majority of the groups.

Furthermore, it was apparent from the groups' sociochemical dialogues that they were involved in chemical meaning making and negotiated what criteria to use to select appropriate symbolic equations for dissolving ionic solids. The course instructor similarly communicated to student groups during dialogical discourse on what counts as chemically justifiable and what counts as appropriate representation of chemical ideas. Thus, there was a collective development of ways of reasoning that was indicative of the student groups negotiating and developing criteria for what counts as an acceptable justification for a chemical phenomenon. These findings are consistent with those recently reported by Becker, Rasmussen, Sweeney, Wawro, Towns and Cole (2012) who studied the development of sociochemical norms in small group setting.

The idea of ionic compounds dissociating into ions was used to develop appropriate particulate drawings of dissolved ionic solids but also as a way to explain the conductivity properties of ionic solids in water. Students often reasoned that salt water will conduct electricity because salts contain ionic bonds which will be "dispersed" when placed in water whereas sugar water will not conduct because sugar contains covalent bonds which will not "disperse" and do not contain "free floating" ions. Not all groups initially subscribed to these ideas, but their recurrent use suggested they become normative within the class discussions.

7.1.2. The development of sociochemical norms - Patterns across the groups

Given that chemical justifications became normative in each group's discourse and were used repeatedly by large numbers of the groups as a guide to select multiple-choice options, I examined the patterns of criteria use across the groups. The results of this analysis showed that the student groups in this study developed criteria that were either based on the physical properties of dissolving ionic solids (i.e., ions, aqueous) or focused on the symbolic presence of water in the given equations. Again, the ways in which the groups used these criteria suggested justifications based on descriptions of either the physical properties of ionic salts or focus on the symbolic features present in the chemical equations became normative across the groups. Interestingly groups who initially used physical properties as criteria ($N = 7$) for selecting appropriate equations for dissolved ionic solids were more likely to choose the correct response than groups who focused on water as a criterion ($N = 3$). In summary, the recurrent use of similar justifications across the ten autonomous groups in the study suggested certain ideas served as normative type of reasoning to explain the physical and chemical properties of dissolved ionic solids.

7.1.3. The identification of sociochemical norms across topics

One of the criteria set above to determine whether ideas became normative in the class was to determine if different groups used the same criterion as justification for different topics. The across group analysis revealed that the ten different groups in this study developed similar criteria to describe what happens to ionic solids placed in water but also to account for the conductivity properties of chemical materials placed in water. Groups used the idea of "dissociation into ions" to describe both the physical properties of dissolving ionic solids and to account for why compounds like sodium iodide (NaI) conduct electricity whereas materials like sucrose ($C_{12}H_{22}O_{12}$) do not.

7.1.4. Shifts in student thinking – the influences of sociochemical norms

The more interesting data in response to the first research question concerned the influence of observed sociochemical norms on individual student's conceptions of dissolving ionic compounds. Two different lines of evidence suggested group thinking during sociochemical dialogues influenced individual student learning. The first came from analysis of data showing what appeared to be evolution in individual thinking when students were confronted with opposing viewpoints with respect to the nature of dissolving ionic solids in water. The second line of evidence came from analysis of a whole class pre-post assessment. The quantitative analysis in the form of pre-posttest assessment following activity completion showed global impact on students' understanding of the dissolution of ionic solids. It was reasoned that since students made public their views and encountered opposing ones in the unfolding sociochemical dialogues, this availed them opportunities to shift their thinking (Smith, 1985).

7.2. Research question 2: the influences of teacher-initiated discourses

Some of the groups in the study changed their thinking after the course instructor intervened or after consulting with other groups in the class. This observation necessitated understanding the instructor's actions when encountering student groups. Analysis revealed two kinds of teacher-initiated discourse – a dialogical discourse and a monologic discourse. Teacher-initiated dialogical discourse occurred as a result of teacher engagement with students in their small group setting while monologic discourse was teacher-centered monologues often delivered before students embarked on new

POGIL ChemActivities. This analysis revealed seven teacher moves during these encounters (Table 5.1):

- *Communicative*: this move communicated to students what counts as chemically justified and what counts as acceptable representations of chemical ideas
- *Confirming*: this move indicated to students that they recognized the right phenomenon (i.e. ions) and/or confirmed the validity of their acts or responses
- *Re-orienting*: this suggested to students to modify their responses or go in a different direction
- *Instructional*: provided direct instructions to students on what to do next
- *Generative*: this move forced students to generate explanations for a given chemical phenomena based on their prior knowledge
- *Linking*: with this move, the instructor provided explicit links between the different representational modes of chemistry
- *Sharing*: with this move, the instructor shared with students information and facts about chemical phenomena

With these practical moves, the instructor communicated arguments to student groups as to what counted as chemically justifiable and acceptable appropriate representations of dissolved ionic solids at the particulate and symbolic levels. She similarly made concerted effort to explicitly link the multiple ways of representing chemical knowledge (i.e. particulate, symbolic, macroscopic, real life experiences, and language) for the students. There were different impacts of the teacher-initiated discourses, however. Dialogical discourses seemed to enhance student conceptions of ionic solids whereas monologic discourses did not seem to help. This assertion is based on the nature of student discourses following each teacher-initiated discourse. There was evidence of shifts in student and whole group thinking during dialogical discourse but no such shifts were observed following teacher-initiated monologic discourses. One possible hypothesis that can account for the different effects of the teacher-initiated discourse has to do with the nature of the practical moves the teacher made during these discourses. The instructor used five of the seven moves described during dialogical discourse – communicative, confirming, re-orienting, instructional, and linking; and four of the seven during monologic discourses – communicative, instructional, generative, and sharing. The moves during dialogical discourses involved knowledge co-construction with the student groups whereas moves during monologic discourse appear to be of the "telling" variety. In summary, the instructor's practical moves influenced the ways in which students were reasoning but certain teacher moves had more impact than the others, depending on the nature of unfolding sociochemical dialogues.

7.3. Research question 3: the effects of POGIL on student learning

The foregoing discussions focused on the role of sociochemical norms on student understanding. The third research question, however, asked how the POGIL materials themselves affected students' understanding of the nature of ionic solids in water. Analysis was mainly based on pre-posttest measures of student achievement. The results suggested the class as a whole performed poorly on measures of pretest assessment but did improve their conceptions of ionic compounds in solution post-POGIL. The data similarly revealed that the student cohorts in this study held wide range of misconceptions related to the nature of aqueous ionic compounds including the idea that ionic compounds react with water to form an acid and a metal oxide; dissolving ionic solids and water morph into a larger individual molecule; ionic solids in water dissociate into charged particles that are covalently bonded to each other; polyatomic ions dissociate into individual segregated ions; ionic solids dissociate in water as neutral atoms or molecules; and confusion of coefficients and subscripts. As noted in chapter two, most of these misconceptions were previously identified in the chemistry education literature (Ebenezer & Erickson, 1996; Naah & Sanger, 2012; Nyachwaya, Mohamed, Roehrig, Wood, Kern & Schneider, 2011; Smith & Metz, 1996; Tien, Tiechert, & Rickey, 2007). However, the misconception that ionic salts dissolve into water and form a large individual molecules was not previously reported. Prevalence of these misconceptions ranged from a low of 3% to a high of 26%. Post-POGIL, however, there appeared to be erosion of these misconception, with the highest recorded percentage for a misconception being 6% in the post-POGIL data vs. a high of 26% in the pre-POGIL data.

Analysis of students' particulate drawings indicated that the majority of students used a molecular framework to depict dissolving ionic compounds at the particulate-level – only 2.3% of the drawings showed appropriate ionic framework while close to 71% were coded as being molecular in the pre-POGIL tasks. In addition to using molecular and ionic frameworks to depict ionic compounds, several drawings were categorized as "other" because they showed inappropriate connections between the atoms or amalgamates of discrete atoms, ions, and molecules as one bonded mass. The frequencies of molecular drawings and other category decreased in the post-POGIL drawings while the frequencies of appropriate drawings for dissolved ionic compounds or those drawings partial understandings increased dramatically.

One disconcerting finding in the data was students' inability to transfer their newly improved understanding of what happens to dissolved ionic compound when the questions were asked under different context – precipitations reactions versus direct questions asking to show what happens to ionic salts dissolved in water. However, this appears to be a larger question of knowledge transfer and what inhibits that transfer, a discussion worthy of further research and analysis.

7.4. Implications and suggestions for future research

The foregoing discussions focused on the role of sociochemical dialogues on student understanding of ionic compounds in water and the effects inquiry-based strategies such as POGIL had on chemistry learning. The discussion on sociochemical norms and the ways in which chemical ideas were used in these cooperative learning groups suggests meaningful learning can be promoted by rational curriculum design, one that takes into consideration the social context of learning and the nature of student-teacher interactions. The students in this class were able to collectively develop criteria on what counts as acceptable and justifiable reasoning for selecting appropriate symbolic equations for dissolving ionic solids and what accounts for the conductivity of chemical materials in water. Their verbalization of their ideas in the POGIL classroom provided opportunities for constructive discourse that enhanced their conceptions of what happens to ionic solids placed in water. The implication for teaching is that understanding the how's and why's of student learning can help chemistry educators understand the dynamics of and the social factors that influence the classroom learning environment. Wu (2002) suggests the "authentic" feature of curriculum needs to emphasize the establishment of social norms (and in this case sociochemical norms) that shape and influence student learning. In setting up scenarios that generate sociochemical dialogues, it is important to consider the structure of inquiry-materials and how that elicits student conceptions of chemical ideas and understandings.

Additionally, the role of the science teacher in classroom discourse is important. This study identified seven moves the course instructor made to scaffold for students what happens to dissolved ionic solids at the different representational levels of chemistry knowledge. Certain teacher moves, when interacting with student cohorts, were more helpful than others. For instance, re-orienting and linking moves during dialogical discourse with student groups appeared to result shifts in student thinking whereas sharing and instructional moves during teacher-initiated monologic discourse were deemed unhelpful. The implication here, then, is that what teachers do and how they act during classroom discourse influences how students develop representational fluency. Worth mentioning here is that the course instructor strived to provide for the students links between their everyday lives, the molecular models they were using to model what happens to dissolved ionic solids, and the multiple representational modes of chemistry representations. Thus, another implication for chemistry teaching is the need to explicitly link multiple representational modes for students. Yes I like this but I am not sure your data support this

The findings for this study provide a backdrop for further research to explore patterns of student reasoning in the context of sociochemical dialogues, how instructional strategies and curricular materials improve student understanding of chemistry, and the role of language and real life experiences for understanding representational fluency in chemistry. Further questions worth pursuing include:

- What promotes effective sociochemical dialogues that result shifts in student thinking?
- Are there specific patterns to curricular materials that promote effective student discourse?
- What accounts for the different impact of teacher-initiated discourses when encountering student groups?
- What discourse patterns in student-initiated sociochemical dialogues promote or constrain student development of criteria to explain given chemical phenomenon, such as the dissolution of ionic solids in water or what counts as acceptable and appropriate representation of chemical ideas at the particulate level.

The nature of the analysis done in this work provides methodological approach to investigate these questions and may provide insights into how classroom discourse in which students interact with other or with their instructors influences students' learning of chemical ideas.

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Appendixes

The appendixes include all the materials used in this study. These were, the POGIL ChemActivity used to target student understanding and representation of compounds at the atomic/molecular level, the pre-test assessment given to students at the first day of classes (there was no grade points associated with this assessment), the post-test assessment embedded to student exams throughout the semester (and hence associated with graded points), and the documentation for human subjects. These materials are organized in the appendixes as follows:

Appendix A: POGIL ChemActivity: Group Report

Appendix B: POGIL ChemActivities: What happens to compounds placed in water?

Appendix C: Pre-test Assessment

Appendix A: Sample Cooperative Group Report Form

Group Report Form

What Happens When Compounds are Added to Water?

Team Members Present (Alphabetically by last name):

1.___________________________ (reflector, activity)

2.___________________________ (presenter)

3.___________________________ (skeptic)

4.___________________________ (recorder)

Team Member Responsibilities:

Team Member 1: Activity reflector, responsible for observing and reflecting on group understanding of this topic (see back side of report).

Team Member 2: Presenter of group consensus answers.

Team Member 3: Skeptic, responsible for asking why (checking to see if all members can explain answers) and checking sig figs.

Team Member 4: Recorder, responsible for writing group consensus answers requested below. The presenter must be able to read and understand these answers.

Note: groups of 3, please combine team member 1 and 3 roles.
Group Consensus Answers to the following questions (Questions will be exactly the same or similar to the appropriately numbered and starred question (***)):

2. ***In the space below, draw a diagram that represents what happens to the sodium chloride (NaCl) matrix when placed in water. Make sure to provide a legend for your drawing or write appropriate chemical symbols inside each atom core.

Before Mixing → *After Mixing*

5. ***Based on your particulate diagrams, which of the following balanced equations shows what happens to methanol (CH_3OH) placed in water?

   a. $CH_3OH\ (l) + OH^{-}\ (aq) \rightarrow CH_3O_2H_2\ (aq)$
   b. $CH_3OH\ (l) \rightarrow CH_3OH\ (aq)$
   c. $CH_3OH(l) \rightarrow C^{4+}\ (aq) + 4H^{+}\ (aq) + O^{2-}\ (aq)$
   d. $CH_3OH(l) + H_2O(l) \rightarrow CO_2(g) + 3H_2(g)$
   e. $CH_3OH\ (l) \rightarrow CH_3^{+}\ (aq) + OH^{-}\ (aq)$

6. ***Based on your observations in Activity 1 and 2 and the ***information*** above, ***predict*** whether or not the following compounds would conduct electricity in aqueous solutions. In your response, ***state clearly this compound "will" or "will not" conduct electricity in aqueous solution*** and provide short explanation for your reasoning.
   a. Solid sodium iodide (NaI) dissolved in water:

   b. Solid sucrose ($C_{12}H_{22}O_{12}$) dissolved in water:

8. ***According to the data in Table 1, what is conductivity of (in LEDs)
   a. 0.1 M sodium chloride (NaCl)? ________________ LEDs
   b. 0.2 M sodium chloride (NaCl)? ________________ LEDs
   c. Explain why the conductivity values of 0.1 M and 0.2 M solutions of sodium chloride (NaCl) are different?

10c. ***Which of the following balanced equations shows what happens to solid $CuCl_2$ when it is placed in water?

i. $CuCl_2\ (s) \rightarrow Cu^{+}\ (aq) + Cl_2^{-}\ (aq)$
ii. $CuCl_2\ (s) + H_2O\ (l) \rightarrow CuO\ (aq) + 2HCl(aq)$
iii. $CuCl_2\ (s) \rightarrow Cu^{2+}\ (aq) + 2Cl^{-}\ (aq)$
iv. $CuCl_2\ (s) \rightarrow Cu\ (aq) + Cl_2\ (aq)$
v. $CuCl_2\ (s) \rightarrow CuCl_2OH\ (aq)$

10d. ***Explain your choice for the balanced equation in the previous question.

Team Member 3 Reflection: Indicate your group's level of confidence in the topics covered in this activity by filling the appropriate bubble based on the following scale:

1. not at all confident
2. slightly confident
3. moderately confident
4. very confident
5. highly confident

Not at all confident ① ② ③ ④ ⑤ **Highly confident**

Do any of your group members have questions about this topic? List at least two questions below.

Appendix B:
POGIL ChemActivity: What Happens When Compounds are Added to Water?

Why?

Recall that an ionic bond forms when there are opposite electrostatic charges – negative and positive charges – that are attracted to each other. For instance, in the ionic compound sodium chloride (NaCl), each positive sodium ion is ionically bonded (or electrostatically bonded) to each of the neighboring negative chloride ions to form a matrix of ions. In contrast, a covalent or molecular bond forms when electrons are shared between a pair of atoms. For instance, in the molecular compound hydrogen (H_2), each hydrogen electron is shared between the two atom centers. Despite having different types of bonding, ionic and molecular compounds can be mixed together to form solutions (or homogeneous mixtures). For instance, table salt (NaCl) can be dissolved in water (H_2O) to form a homogeneous mixture.

Learning Objectives

At the end of this activity you should be able to:

- understand the physical properties of various compounds dissolved in water
- relate information in chemical formulas and macroscopic observations to what happens at the atomic/molecular level
- relate solution conductivity to chemical formulas and particles

Success Criteria

- Ability to predict the physical behavior of compounds dissolved in water
- Ability to write balanced chemical equations for compounds dissolved in water
- Ability to translate macroscopic data and observations into particulate level understanding
- Ability to show particulate level understanding of what happens to compounds dissolved in water

Pre-Requisite Information

- How to write and balance chemical equations
- Understanding of chemical bonds (ionic versus covalent)
- Working understanding of the nature of solutions
- Knowing what *s*, *l*, *g*, and *aq* mean and stand for in chemical reactions.
- Working knowledge of molarity (M) or (mol/L)

3D Molecular Design Kit Activity. *You will be provided with a kit that has the following contents:16-18 water (H_2O) molecules,4 sodium ions (Na^+), 4 chloride ions (Cl^-), and a molecule of methanol (CH_3OH). All atoms are magnetized although the magnitude of the charges is not reflected in the model — e.g., some particles have full positive charge whereas others have partial charge but all of them are equally magnetized. Your group will also receive a tray to place the atoms, ions, and molecules. You will use this molecular kit to investigate what happens to compounds when we put them in water.*

Activity 1: What happens to ionic compounds when you put them in water?

1. Your instructor will demonstrate the dissolution of sodium chloride (NaCl) and methanol (CH_3OH) in water. Describe, in your own words, the appearance of chemicals before and after the addition of the chemicals in water.

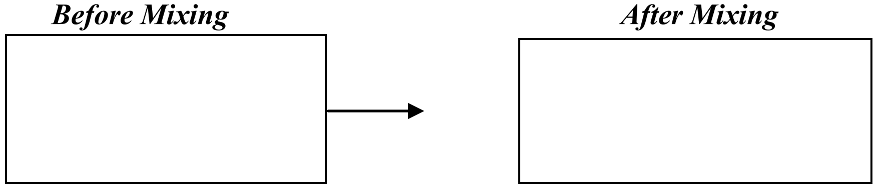
a. Verbal description of sodium chloride (NaCl) before and after adding it to water

b. Verbal description of methanol (CH_3OH) before and after adding it to water

***DIRECTIONS**: Obtain a matrix of sodium chloride (NaCl) from your 3D Molecular Design Kit. Mix the compounds in your bag by using your hands to break up and rearrange any particles that are magnetically attracted to one another.*

2. ***In the space below, draw a diagram that represents what happened to the sodium chloride (NaCl) matrix when placed in water. Make sure to provide a legend for your drawing or write appropriate symbols inside each atom core.

Before Mixing ***After Mixing***



3. Based on your particulate diagrams, which of the following balanced equations shows what happens to sodium chloride (NaCl) placed in water?

   a. NaCl *(s)* → Na *(aq)* + Cl *(aq)*
   b. 2NaCl *(s)* + H_2O *(l)* → 2HCl *(aq)* + Na_2O*(aq)*
   c. NaCl *(s)* → Na^+*(aq)* + Cl^-*(aq)*
   d. NaCl *(s)* → Na^+*(s)* + Cl_2^-*(s)*
   e. NaCl *(s)* → Na^+*(s)* + Cl^-*(s)*

POGIL ChemActivity 2: What happens to molecular compounds when you put them in water?

***DIRECTIONS:** Obtain a methanol molecule (CH_3OH) from your 3D Molecular Design Kit. Mix the compounds in your bag by using your hands to break up and rearrange any particles that are magnetically attracted to one another.*

4. In the space below, draw diagrams that represent what happened to methanol (CH_3OH) when placed in water. Make sure to provide a legend for your drawing or write appropriate chemical symbols inside each particle.

5. ***Based on your particulate diagrams, which of the following balanced equations shows what happened to methanol (CH_3OH) placed in water?

   a. $CH_3OH\ (l) + OH^{-}\ (aq) \rightarrow CH_3O_2H_2\ (aq)$
   b. $CH_3OH\ (l) \rightarrow CH_3OH\ (aq)$
   c. $CH_3OH(l) \rightarrow C^{4+}\ (aq) + 4H^{+}\ (aq) + O^{2-}\ (aq)$
   d. $CH_3OH(l) + H_2O(l) \rightarrow CO_2(g) + 3H_2(g)$
   e. $CH_3OH\ (l) \rightarrow CH_3^{+}\ (aq) + OH^{-}\ (aq)$

Information
When chemical compounds are dissolved in water, they appear to disappear. In reality, the compounds generate homogeneous mixture. One way to test this mixture is through electrical conductivity — a solution will conduct electricity when freely moving ions are present.

Predictions for Next Section of the Activity:

6. ***Based on your observations in Activity 1 and 2 and the ***information*** above, ***predict*** whether or not the following compounds would conduct electricity in aqueous solutions. In your response, ***state clearly this compound "will" or "will not" conduct electricity in aqueous solution*** and provide short explanation for your reasoning.

   a. Solid sodium iodide (NaI) dissolved in water:

   b. Solid sucrose ($C_{12}H_{22}O_{12}$) dissolved in water:

Please do not go onto the rest of the activity until you have made your predictions!!!

POGIL ChemActivity 3: What happens to the conductivity of water when compounds are dissolved in it?

The conductance of aqueous solutions can be measured using a devise that displays conductivity values. There are many different devices used for measuring conductivity. One type of device has lights (LEDs) that light up when a solution conducts electricity. The number of lit LEDs is proportional to the conductivity of the ions in the dissolved solution.

Your instructor is going to demonstrate the conductivity of water before and after the addition of sodium chloride (NaCl). Describe your observations in the space below.

Conductivity before addition of NaCl ***Conductivity after addition of NaCl***

Critical Thinking Questions

Refer to the information in Table 1 below to answer questions 7 - 10

Table 1: Conductivity values of several chemical compounds in water.

Experiment #	Solution (M = mol/L)	Observation	Conductivity in Water (# of LEDs lighting up)
1	0.1 M sodium chloride (NaCl)	Clear, colorless solution	2
2	0.2 M sodium chloride (NaCl)	Clear, colorless solution	4
3	0.1 M sodium iodide (NaI)	Clear, colorless solution	2
4	0.1 M ammonium chloride (NH_4Cl)	Clear, colorless solution	2
5	0.1 M sodium sulfate (Na_2SO_4)	Clear, colorless solution	3
6	0.2 M sodium sulfate (Na_2SO_4)	Clear, colorless solution	6
7	0.1 M copper (II) chloride ($CuCl_2$)	Clear/blue-green solution	3
8	Deionized water (H_2O)	Clear, colorless solution	negligible
9	0.1 M sucrose ($C_{12}H_{22}O_{12}$)	Clear, colorless solution	negligible
10	0.1 M methanol (CH_3CH_2OH)	Clear, colorless solution	negligible
11	0.1 M isopropanol (C_3H_7OH)	Clear, colorless solution	negligible

7. List below formulas of compounds that conduct electricity and those that do not when dissolved in water (refer to Table 1).

8. Based on your response above, what type of compounds conduct electricity when dissolved in water?

9. ***According to the data in Table 1, what is conductivity of (in LEDs)

   d. 0.1 M sodium chloride (NaCl)? ________________ LEDs
   e. 0.2 M sodium chloride (NaCl)? ________________ LEDs
   f. Explain why the conductivity values of 0.1 M and 0.2 M solutions of sodium chloride (NaCl) are different?

10. Consider again the data in Table 1.

   a. What is the conductivity of 0.1 M sodium sulfate (Na_2SO_4) ____________________ (LEDs)
   b. In the space below, draw a diagram that represents what happens to solid sodium sulfate (Na_2SO_4) when it is placed in water. Make sure to provide a legend for your drawing or write appropriate chemical symbols inside each atom core.

   Before Mixing → ***After Mixing***

   c. Which of the following balanced equations shows what happens to solid Na_2SO_4 when it is placed in water?

      i. $Na_2SO_4\,(s) \rightarrow 2Na^{+}(aq) + SO_4^{2-}(aq)$
      ii. $Na_2SO_4\,(s) \rightarrow Na_2^{+}(aq) + SO_4^{2-}(aq)$
      iii. $Na_2SO_4\,(s) + H_2O\,(l) \rightarrow Na_2O(aq) + H_2SO_4(aq)$
      iv. $Na_2SO_4\,(s) \rightarrow 2Na^{+}(aq) + S^{2-}\,(aq) + 4\,O^{2-}(aq)$
      v. $Na_2SO_4\,(s) + H_2O\,(l) \rightarrow Na_2OH_2SO_4(aq)$

   d. Is the conductivity of 0.2 M sodium sulfate (Na_2SO_4) the same or different than that of 0.1 M (Na_2SO_4). Explain.

11. Consider again the data in Table 1.

a. What is the conductivity of 0.1 M copper (II) chloride ($CuCl_2$)?

____

b. In the space below, draw a diagram that represents what happens to solid copper (II) chloride ($CuCl_2$) when it is placed in water. Make sure to provide a legend for your drawing or write appropriate chemical symbols inside each atom core.

Before Mixing ***After Mixing***

c. ***Which of the following balanced equations shows what happens to solid $CuCl_2$ when it is placed in water?

vi. $CuCl_2\ (s) \rightarrow Cu^{+}\ (aq) + Cl_2^{-}\ (aq)$
vii. $CuCl_2\ (s) + H_2O\ (l) \rightarrow CuO\ (aq) + 2HCl(aq)$
viii. $CuCl_2\ (s) \rightarrow Cu^{2+}\ (aq) + 2Cl^{-}\ (aq)$
ix. $CuCl_2\ (s) \rightarrow Cu\ (aq) + Cl_2\ (aq)$
x. $CuCl_2\ (s) \rightarrow CuCl_2OH\ (aq)$

d. ***Explain your choice for the balanced equation in the previous question.

Take-Home Exercises

12. Show calculations to prove that
    a. A solution containing 2.70 g of NH_4Cl dissolved in 500 mL of water has similar conductivity values (in LEDs) to a solution containing 2.94 g of NaCl dissolved in 500 mL of water.

    b. based on the molarity concentrations you calculated, what are the predicted conductivity values (in LEDs)? [Hint: use the data in table 1].

13. Diagram the particulate representations of NaCl and NH_4Cl to explain their similar/different conductivities in the previous question?

14. By definition, physical processes involve rearrangement of particles but not changes to the particles themselves.
    g. Is dissolving an ionic compound in water a physical process? Please explain your answer.

    h. Is dissolving a molecular compound in water a physical process? Please explain your answer.

Appendix C: Complete Early Pretest Items

Semester Pre-Assessment

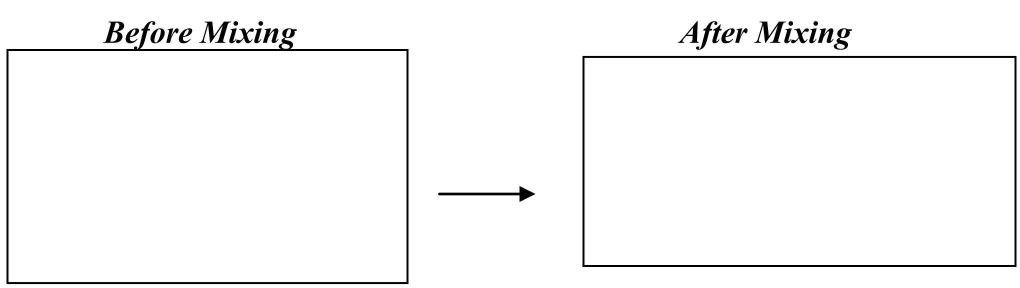
This is an instrument developed to test your present knowledge about some scientific concepts taught in chemistry courses. The results of this test will have no effect on your grade in your chemistry class but they will be used to help organize instruction for this course. Please answer to the best of your knowledge and work individually. Thank you.

1. Suppose you placed a spoonful of solid potassium iodide crystals (KI) in water (H_2O) and stirred until the crystals disappeared.

a. Please **explain in words** what happens when the solid KI disappears in water.

b. **Write a balanced chemical equation** that represents what happens when the solid KI disappears in water.

c. **Draw a diagram** that represents what you think you might see if you were able to see the atoms, molecules, and/or ions present in the balanced chemical equation described in part b. Remember to draw the correct proportions of atoms, molecules, and/or ions. Make sure to provide a legend for your drawing or write appropriate chemical symbols inside each atom core



2. Silver Nitrate ($AgNO_3$) reacts with Calcium Chloride ($CaCl_2$) to form Silver Chloride ($AgCl$) and Calcium Nitrate ($Ca(NO_3)_2$). The reaction is represented by the ***unbalanced*** chemical equation below:

__ $AgNO_{3(aq)}$ + __ $CaCl_{2(aq)}$ $\rightarrow$ __ $AgCl_{(s)}$ +__ $Ca(NO_3)_{2\ (aq)}$

a. Write the appropriate numbers in the blanks to balance the chemical equation

b. In the space below, draw diagrams that represent what you think you might see of you were able to see the atoms, molecules or ions involved in the chemical equation above. Remember to draw the correct number of atoms, molecules or ions of each reactant and each product.

Reactants

Products

Reflection:

a. In as much detail as you can, what words, concepts, and/or ideas did you struggle with in answering the two questions in this assessment?

b. In as much detail as you can, what words, concepts, and/or ideas were you confident with in answering the two questions in this assessment.