Collaborative Discourse and the Modeling of Solution Chemistry with Magnetic 3D Physical Models – Impact and Characterization

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Introduction

A significant body of the literature in science education examines students' conceptions of the dissolution of ionic solids in water (see Ebenezer 2001; Kabapinar et al. 2004; Kelly and Jones 2007; Naah and Sanger 2013). These studies have shown that students often lack proper understanding of the particulate nature of dissolving materials and hold numerous misconceptions about the dissolution process (see Calyk et al. 2005, for a comprehensive review of this topic). Consequently, chemical educators have explored several instructional strategies to address this issue including the use of multimedia and computer animations (Ardac and Akaygun 2004; Ebenezer 2001; Kelly and Jones 2007, 2008; Naah and Sanger 2013), inquiry-based instruction (Kaartinen and Kumpulainen 2002; Kabapinar et al. 2004), and hands-on laboratory activities (Bruck et al. 2010; Tien et al. 2007). A central feature of these various strategies is the use of modeling, whether computer-based or student-generated, to influence students' understanding of the dissolution process. However, most of the studies that look at the effects of modeling instructions in chemistry focus on the effects of the modeling activity itself on student learning (e.g., whether there is empirical evidence to suggest the effectiveness of the modeling activity on student understanding of the dissolution process) and not necessarily how student engagement and classroom talk during the modeling activities effect student learning. Similarly, the impact of physical three-dimensional (3D) models on students' understanding of the dissolution process has not been fully explored (see Bruck et al. 2010). Thus, this study addresses students' interactions with 3D models and its impact on student understanding of the dissolution process. In the paper, we describe the ways in which the use of tactile 3D magnetic models during a cooperative inquiry-based activity on chemical bonding prompted classroom discourse on what counts as chemically justifiable and appropriate representations of dissolved ionic solids in water. We use the 3D magnetic molecular models to research the role of models in science teaching, the nature of classroom discourse initiated by modeling activities, and unfolding changes in student conceptions and ultimately student learning. The research questions that guided this study were:

1. What is the nature of classroom discourse prompted by the use of physical 3D magnetic molecular models representing the dissolution of ionic solids in water?
2. What impact did the use of 3D magnetic models have on students' understanding of the process of dissolving ionic solids in water?

Our analysis of the nature of classroom discourse initiated by modeling activities addresses two areas: (1) the characteristic features of students' engagement (i.e., discourse) in modeling that are critical to their science learning; and (2) how sensory-based physical models (i.e., the use of 3D magnetic molecular models) can transform teaching and learning as students discuss and use models. We describe both the potential and the limitations of these 3D models for teaching the fundamental concept of the dissolution process in chemistry.

Background Literature

Modeling in School Science

Modeling is arguably one of the most common pedagogical tools used in science classrooms the world over. Their use to represent scientific information, explain and describe ideas, or provide means of visualizing abstract scientific concepts is consistently advocated in national science standards documents (AAAS, 1993; NRC, 1996, 2012). The new Next Generation Science Standards (NRC, 2013) specifically call for engaging students in developing and using models, constructing explanations, and engaging in arguments from evidence. The framework for K-12 science education (NRC 2012), which informed the development of the NGSS standards, states the following about the use of models in science:

> *"Science often involves the construction and use of a wide variety of models and simulations to help develop explanations about natural phenomena. Models make it possible to go beyond observables and imagine a world not yet seen. Models enable predictions of the form "if . . . then . . . therefore" to be made in order to test hypothetical explanations." (NRC 2012, p. 50)*

This research is aligned with Campbell et al.'s (2011) definition of modeling as a "mechanism of cohesively facilitating student learning about science content, science process, and the nature of science in a more holistic and relevant manner" (p. 261). Facilitation, in this study, occurred through activities that included tactile experiences with three-dimensional physical models of ionic solids to model their dissolving in water. We also drew on

Windschitl et al.'s (2008) definition of models as "a comprehensive systems of explanations that provide crucial frames for hypotheses testing, [and] act as referents in interpreting information" (p. 945). By this definition, the 3D models in this study serve as referents for interpreting information about the process of dissolving chemicals in water.

Model-based teaching is especially ubiquitous in the chemical sciences where models are used to represent abstract chemical ideas such as the nature of atomic and sub-atomic particles, molecular shapes, molecular polarity, and a plethora of other chemical concepts (Chittleborough and Treagust 2008). However, research has consistently shown that students lack conceptual understanding of these ideas and struggle with relating macroscopic observations and symbolic descriptions of chemical concepts with their particulate representations (Gabel 1999; Harrison and Treagust 2002; Johnstone 1991; Talanquer 2011). Particulate-level modeling activities, especially those coupled to inquiry practices (Bridle and Yezierski, 2012; Davidowitz, et al. 2010), have recently shown promise in enhancing students' representational competency in chemistry, especially with respect to solution chemistry.

Modeling Solution Chemistry

Studies have shown positive effects of modeling on students' particulate-level understanding of solution chemistry (Ardac and Akaygun 2004; Ebenezer 2001; Kelly and Jones 2007, 2008; Naah and Sanger 2013; Smith and Metz 1996). For example, Ebenezer (2001) used a multimedia environment to explore grade11chemistry students' conceptions of table salt dissolved in water. The animations in the multimedia environment "enabled students to visualize how melting is different from dissolving, how ions are formed, and how hydration took place" (p. 87). Kelly and Jones (2007, 2008) similarly reported that viewing dynamic animations of a sodium chloride model enhanced students' understanding of the structure and function of salts in water. Their students, however, were unable to transfer their newly improved conceptions developed from the particulate animations to other aqueous solutions in a subsequent assessment.

Despite the improvements in student understanding noted in the foregoing studies, there are difficulties with the use of computer animations and other multimedia environments for modeling the dissolution process. Kelly and Jones (2007) particularly highlighted the importance of including interactive features into computer-animated chemistry concepts to help students better understand the processes portrayed by the animations. Ebenezer (2001) similarly noted students encountered difficulties related to three areas within the multimedia environment: ion formation, the polar nature of water molecules, and hydration processes. In a more recent study, Naah and Sanger (2013) obtained results that suggested the use of animated particulate equations for dissolved ionic solids in water were distracting for students, as they diverted student attention away "from focusing on the important or relevant chemical concepts that the animation is intending to convey" (p. 111).

In the present study, we examined the utility of 3D physical models for improving student understanding of the dissolution concept. The 3D models differ from the computer animations used in the foregoing studies in two important ways. First, they provides tactile experiences based on electromagnetic properties and touch-sensory feedback (3D Molecular Designs). This is important since one of the limitations of computer animations and student-generated drawings is that forces such as attractions between ionic centers are not easily observable in virtual environments or the one-dimensional ball-and-stick models commonly found in chemistry classrooms (Bivall et al. 2011; Comai et al. 2010; Sankaranarayanan, et al. 2003). With touch sensory models, users can feel these forces through sensory feedback (Bivall et al. 2011). Second, the magnetic models do not require the use of computers or animated features. Animations and dynamic motions can be distracting in certain instances (see Kelly and Jones 2008; Naah and Sanger 2013). Thus, excluding extraneous information such as animated motions for depicting molecular interactivity can diminish occurrences of cognitive overload (Naah and Sanger 2013; Sweller 2008). Physical 3D models have the potential to limit the amount of extraneous information that can interfere with the aims of modeling activities – in this case to better understand the dissolution process.

Generating Discourse through Modeling

One way 3D magnetic models can transform the teaching of chemical ideas is by fostering classroom discourse that affords students opportunities to discuss and negotiate the meaning of chemical symbolism, terminology, and representational forms (Kozma 2000; Wu et al. 2001). In this paper, we use the construct of sociochemical dialogues (Warfa et al. 2014) to identify the characteristic features of student discourse promoted by modeling activities. As we have described elsewhere (Warfa et al. 2014), sociochemical dialogues refer to the specific nature of classroom talk in a learning environment regulated by discipline-specific norms on what counts as acceptable and justifiable chemical reasoning. Becker et al. (2013) coined the term sociochemical norms to describe the nature of discipline-specific norms and tacit ways of reasoning about chemical ideas that occur specifically in chemistry classrooms. We have suggested (Warfa et al. 2014) that sociochemical dialogues is related to sociochemical norms in that the former reflects dialogues regulated by class-established norms as envisioned by Becker et al. (2013). Our previous work did not specifically attend to the role of modeling within the students' dialogue. We therefore extend our analysis in this paper to discuss how modeling shaped classroom discourse practices. In using sociochemical norms as theoretical lens, we examined qualitatively how group interactions and discourse mediated student learning, focusing on the effects of explanations and dialogical exchanges (Nussbaum, 2008) rather than whether there was evidence of claim, data, and warrant (Toulmin, 1958; Becker et al. 2013).

Theoretical Perspectives

Our analysis of classroom sociochemical dialogs and the overall study was guided by symbolic interactionism (Blumer 1969) and constructivist theories of learning, including the conceptual change model (Posner, et al. 1982; Strike and Posner 1985). In the symbolic interactionist perspective, meaning-making is perceived to occur through social acts that lead to the collective development of common definitions (Bogden and Bilken 2003; Yackel and Cobb 1996). This is particularly true when, as in this study, small group learning dynamics is the pedagogical approach of choice in the classroom. The conceptual change model suggests several conditions must be met in order to bring about a change in students with respect to a concept such as the dissolution process (Calyk, et al. 2005; Duit and Treagust 2003; Hewson and Thorley 1989). Students must be dissatisfied with their existing model, the new conceptions must appear more plausible and attractive, and they must have explanatory and predictive power (Hewson and Thorley 1989; Vosniadou 2007). Students must be actively engaged and allowed to construct these more appropriate conceptions (Vosniadou 2007). The use of magnetic models in this study was intended to better facilitate students' understanding of the dissolution process and to help them construct more appropriate conceptions of the dissolution process.

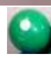
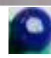
Methods

Context

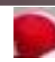
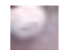
This study was part of a larger research project in which we developed and implemented a series of Process Oriented Guided Inquiry Learning (POGIL) activities, called POGIL ChemActivities, in a first semester chemistry college classroom. POGIL is a cooperative inquiry-based pedagogy championed in chemistry departments since mid-1990s (Farrell, et al. 1999). During POGIL activities, students work cooperatively in small groups on guided materials that emphasize understanding core chemical concepts and developing process skills (Farrell, et al. 1999). Within the small cooperative groups the students take up specific roles such as facilitator, spokesperson, recorder, and process analysts. In this context, the role of the facilitator is to keep groups on task and encourage/promote participation from all members of the group. The spokesperson seeks group input or other groups' input before consulting the course instructor and prepares to articulate group questions and responses for whole class discussion. The recorder regularly checks with group members to make sure that all group members' are consistent and through as well as writing group consensus answers on a group report form. The process analyst reports to their group regarding group performance at least one time during the activity as well as at the end. The particular POGIL ChemActivities in this study were designed to target commonly found student misconceptions about molecular and ionic bonding (Nyachwaya et al. 2011; Naah and Sanger 2012, 2013; Taber, 1998). These activities were reviewed and approved by the POGIL Project (www.pogil.org) and highlighted three specific approaches to teaching the concept of dissolution (Warfa et al. 2014):

1. use of multiple representations (macroscopic, particulate, symbolic, and real life experiences) to better facilitate student understanding of the particulate nature of matter
2. use of 3D magnetic models to provide tangible experiences representing the dissolution process at the atomic/molecular level
3. the interpretation of chemical data, in the form of models and tabulated conductivity values, for hypothesis testing and generation (Windschitl et al. 2008)

To provide tangible modeling experiences, each group received a model kit containing a matrix of four sodium and four chloride ions and eighteen water molecules (H_2O). Magnets were embedded into the poles of sodium and chloride ions and the hydrogen and oxygen models of water (3D Molecular Designs, 2013) to simulate the attractions between the ions and polar water molecules. Figure 1 shows a picture of the NaCl matrix, water molecules, and the instruction students received to use the models during the activity. Magnetic models of ionic compounds (NaCl) were breakable by hand while molecularly bonded compounds (e.g., H_2O) were permanently attached and could not be taken apart without an external force. The use of electromagnetic properties of the models allowed students to model intermolecular forces such as electrostatic attractions between opposing charges. That is, the magnets helped students experience what the ion-dipole interactions (between positive of sodium ion and partial negative dipole of oxygen, and the negative of chloride ion and partial positive of hydrogen) charges feel like.

 = Cl⁻ ,  = Na⁺

A matrix of sodium chloride (NaCl)

 = O ,  = H

Water molecules

3D Molecular Kit Activity 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. Diagram what you see before and after mixing

Fig. 1 Pictures of the 3D sodium chloride (NaCl) matrix, water (H_2O) molecules, and accompanying instructions used to model the dissolution of ionic solids in water.

Instructional Sequence of the POGIL ChemActivities

The POGIL ChemActivities in this study began with student observation of instructor-led macroscopic demonstrations of a solid sodium chloride (NaCl) stirred in water. Following this demonstration, students were asked to write out verbal description of the macroscopic processes they observed in their POGIL worksheet. A subsequent open-ended question asked the students to generate before and after particulate drawings of a solid sodium chloride dissolved in water. During this phase of the activities, the students were modeling the particulate processes with the magnetic molecular models described above. A third sequential question asked the students to select from given multiple-choice options, and based on their particulate diagrams, a balanced symbolic equation that shows what happens to NaCl placed in water. The multiple-choice options were:

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. $NaCl\ (s) \rightarrow Na^+(s) + Cl^-(s)$

The instructor-led demonstrations were utilized as a means to macroscopically demonstrate the dissolution process and to link real life experiences to the dissolution process. The particulate and the symbolic representations were sequenced to reinforce the importance of particulate-level understanding before symbolically representing the dissolution process.

Data Collection

There were three sources for data collection: 1) audio-recorded conversations of ten groups completing the POGIL ChemActivity described above; 2) written classroom artifacts (e.g., worksheets, group reports, etc), and; 3) researcher observations and field notes. The audio-recordings were done during three discussion sessions in a first-semester college chemistry classroom taught by one of the authors. While there were 20 different cooperative groups in the class, a final convenient sample (Creswell, 2003) of ten groups consisting of 3-4 students was used in the study. 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, data not shown).

The study we report here was approved by our institutions' Internal Review Boards (IRB). All participants consented to participate in this study, allowing us to record their conversations and collect artifacts of their work, as well as monitor their interactions during group work. Their dialogues were transcribed verbatim and these transcripts serve as the primary source of data. Classroom artifacts, such as group particulate drawings on activity worksheets and classroom observations, provided secondary reference points for data analysis.

To illustrate how modeling prompted group discourse on what counts as chemically justifiable and appropriate representations of dissolution processes, we present here three case studies, from Group A, Group B, and Group C, of the larger data set. We selected these cases based on the extent to which model-based reasoning was evident in the groups' sociochemical dialogues. More specifically, we use the case of Group A to examine how students used the 3D magnets to model particulate representations of sodium chloride before mixing it with water. We similarly use the case of Group B to examine how 3D models prompted discourse when student groups were generating "after particulate drawings" of dissolved NaCl. Finally, we selected Group C to illustrate how the use of 3D models dissuaded students from selecting incorrect symbolic equations representing the dissolution process. These cases most closely matched the average response from all ten groups and are representative of all the cases.

Data Analysis

To analyze the data we identified all student–student or student–teacher exchanges in which reference to models was evident in their dialogues using the coding scheme shown in Table 1 and described below. An example of such exchange is a student claim, in reference to the 3D models of water, that "*the water molecules [after mixing] didn't break though*" and a follow-up response of "*that is true*" from another student, and a continuation of this dialogue within their group. Once we identified a given dialogue as an appropriate for analysis, we segmented the dialogue into episodes, defined as an independent unit consisting of sequences of statements or exchanges between dialoging parties (Gee & Green, 1998). Episode boundaries were determined by shifts in what was discussed, such as the initiation of a new topic or new aspects of the same topic – for example, a shift from generating particulate drawings of dissolved ionic solids to a discussion on how to represent the dissolution process symbolically. For the purposes of readability, all statements in an episode were sequentially numbered, with the code LN indicating the line number in a given episode.

Table 1 shows the coding scheme we used to analyze the data in each episode. There were three codes that we used to categorize the dialogues featured in the episodes: 1) modeling activity, 2) teacher scaffolding move, and 3) statement identification. We used the code "modeling activity" whenever student talk or teacher instruction involved references to the 3D models or the use of modeling to propose an explanation. We used the code "teacher scaffolding move" to examine student-teacher exchanges and the teacher's practical moves during those exchanges. As we described elsewhere (see Warfa et al. 2014), teacher's practical moves included communicative moves, which communicated to students what was an acceptable chemical explanation; a linking move, which attempted to link for students different chemical representations, and; re-orienting moves, which re-directed students to look elsewhere for appropriate explanations of a chemical phenomenon (Warfa et al. 2014). Finally, we used statement identification types to help us determine whether groups were engaged in negotiation and meaning making processes.

Table 1 Codes used for data analysis and their purpose

Code	Purpose
Modeling Activity	Features student talk or teacher instruction involving references to the 3D models and use of modeling to understand the dissolution process
Teacher Scaffolding Moves	Describes the nature of teacher's practical moves during instruction and includes communicative moves, linking moves, and re-orienting moves (see Warfa et al, 2014, for full description)
Statement Identification (i.e., confirmatory responses, acknowledgement statements, clarification seeking statements)	Helps identify the nature of student dialogs and as evidence of group negotiation of meaning making

Reliability

To establish reliability, two researchers coded an episode from one of the groups together to establish consistent use of the coding scheme shown in Table 1. The researchers subsequently coded a second episode individually. Inter-rater reliability based on percent agreement was 91.7%. Other research members coded different episodes and again inter-rater reliability was established. Once a level of consistency in code use was established, one researcher coded the remaining data, with an ongoing dialogue and discussion with the research team.

Findings

Our analysis of the sociochemical dialogs showed the three student groups in this study used the 3D models to generate appropriate chemical representations of solution chemistry at the particulate and symbolic levels. There was also evidence to suggest model-initiated discourses dissuaded student groups from selecting common misconceptions about dissolution processes reported in the literature (Calyk, et al. 2005; Naah and Sanger 2012, 2013) and used as distractors for multiple-choice questions in this study. The following section describes how modeling prompted discourses and dissuaded students from selecting these common misconceptions. This includes analysis of dialogical interchanges between the course instructor and student groups in the study. In each case, we note the gender make-up and the specific roles student members play (see the background literature section) in their larger group. This is worth noting since the literature in cooperative learning indicates gender composition and make-up is an important factor in group cohesiveness and success (see Johnson, Johnson, and Smith, 1991; Felder and Brent, 2001), something that may influence a group's sociochemical dialogues.

Modeling Particulate Representations of NaCl and Water before Mixing – The Case of Group A

The first case comes from Group A, a group of three female students (*S1, S2, and S3)* each playing a specific cooperative role – *S1* was the group's facilitator, *S2* the spokesperson, and *S3* the group's recorder. We selected Group A to examine how students were using the 3D magnetic models to model particulate representations of sodium chloride before mixing it with water molecules. As noted in the method's section, the group's response was representative of the other groups. Members of this group embarked on this exercise after class discussion following macroscopic observations of the course instructor physically stirring sodium chloride in water. Table 2 shows the group's sociochemical dialog and discursive practices as they attempt to generate particulate drawings of the "before mixing" process.

Table 2 Group A's dialog on drawing "before mixing" particulate diagrams of NaCl and H_2O

	Dialog	Codes
1	T: Make sure you draw a before and after picture.	*Teacher instructional move*
2	S1: Got some water and sodium chloride [refers to model kit].	*Student modeling activity*
3	S2: We're going to draw them in nice big chunks. So there's four Cl's, right? Is Cl the bigger one? I think it's smaller.	*Clarification seeking & group consensus checking statements*

4	S1: Wouldn't it be bigger? It has bigger protons in it. There are four in each, right?	*Follow-up response; consensus checking statement*
5	S2: How many H_2O's? 18. Are we drawing them in their own little glob?	*Procedural talk*
6	S1: I'm not labeling all of these.	*Procedural talk*

In the opening statement of the dialog, the teacher (*T*) instructed the students to make sure to "draw a before and after picture" of NaCl and water. *S2*'s suggestion to draw NaCl and water as "nice big chunks" (LN 3) was prompted by the way these chemicals were represented in the 3D model kit (see Figure 1). The dialogical exchange between *S2* and *S1* in lines 3 and 4 reveals how modeling initiated student discourse. In line 3, *S2* wonders about the number of chlorides in the model and makes reference to the size of atoms in the model – "so there's four Cl's, right? Is Cl the bigger one? I think it's the smaller one." In the kit, the relative size of the ions was reflected in the models; the chloride ion had a bigger size than the sodium ion. In response to *S2, S1* asks rhetorically "wouldn't it be bigger?" and proceeds to provide a chemical justification for why chlorine should be the bigger one – "because it has bigger protons in it" (LN 4). In this exchange, the students were thinking about providing particulate-level explanations for claims about the relative size of atoms and ions. In spite of the misconception apparent in the students' claim, this particular exchange was prompted by model use. That is, reasoning and discussion about the size of atoms was direct result of a discourse initiated by modeling activities.

Following their exchange, the students in Group A drew NaCl and H_2O as "little glob[s]" (LN 5) separated in space (see Figure 2). However, their initial drawing showed sodium and chloride ions as neutral atoms (data not shown). The course instructor noticed this discrepancy in their drawing and intervened. Figure 2 shows the sociochemical dialog that unfolded between the instructor and the students as well as the group's final particulate drawing of the "before mixing" process.

	Dialogue	**Commentary**
7	T: Let's look at your label here. You call it Na and Cl. Are they atoms or are they ions?	*Teacher scaffolding move – communicative (Warfa et al. 2014)*
8	Group: Ions.	*Group confirmatory response*
9	T: Ions. And how do we show that?	*Teacher scaffolding move – reorienting (Warfa et al. 2014)*
10	Groups: Plus's and minus's.	*Group confirmatory response*
11	T: Does that make a big difference in your labels?	*Teacher scaffolding move – linking*
12	Group: Yeah.	*Group acknowledgement statement*
13	T: Okay.	*Teacher acknowledgement statement*

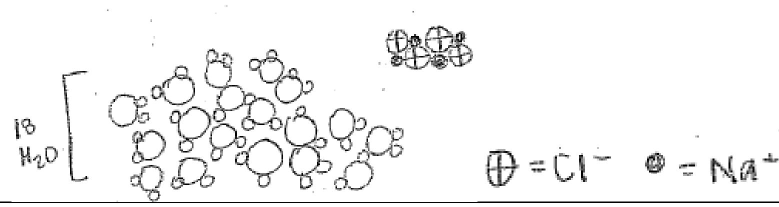


Fig. 2 Sociochemical dialog involving course instructor and Group A and the group's "before mixing" particulate drawings of NaCl and Water.

As is evident in the exchange shown in Figure 2, the teacher made several practical moves that communicated to the students what counts as acceptable particulate representation of a solid sodium chloride. This includes the scaffolding moves in lines 7 and 9 in which the instructor communicates to the students *what counts* as an appropriate particulate representation of ionic compounds ("are they atoms or ions" (LN 7)) and how to represent that knowledge pictorially. That is, the instructor played an important role during model-initiated discourse, interacting with student groups and prompting discourse that appealed to the use of particulate-level explanations for the dissolution processes the students were modeling. This discourse led to student drawings showing an appropriate particulate representation of solid ionic compounds. That is, the students' final drawing in Figure 2 shows appropriate relative sizes of ions and atoms in the system (Na^+ and Cl^- in NaCl, and H and O in H_2O), a lattice with alternating positive and negative ionic centers to represent solid NaCl, and water molecules in their scientifically accepted bent molecular shape. This finding is important in light of well-documented student difficulties with respect to their representation of atomic sizes and ions (*e.g.*, Nyachwaya et al. 2011; Coll and Treagust, 2003).

Modeling Particulate Representations of NaCl and Water after Mixing – The Case of Group B

Our second case comes from Group B, a group consisting of four female students. Student 1 (*S1*) was the group's facilitator, *S2* the spokesperson, *S3* the recorder, and *S4* the group's process analyst/skeptic. We selected Group B to illustrate how 3D models prompted discourse when student groups were generating "after particulate drawings" of NaCl and water mixed. The students were routinely using the 3D models to describe how NaCl separates apart into individual ions and used language that referred to connectivity of atoms (*e.g.*, the Na in NaCl is attracted to the O in H_2O), chemical bonding modes, and hydration processes of ionic centers by water molecules. That is, the 3D models prompted discourse laden with particulate-level descriptions of the dissolution process, including claims about the connectivity and spacing of particles involved in the dissolution process. Table 3 shows the first episode of the group's dialog as they generated "after mixing" particulate drawings of NaCl and water.

Table 3 Group B's dialog on drawing "after mixing" particulate diagrams of NaCl and H_2O

Dialog	Commentary

14	S4: So, then after mixing …	*Modeling activity*
15	S1: It's kind of a huge globular thing	*Information sharing statement*
16	S4: Are the Na and Cl connected to the hydrogen or to the...?	*Clarification seeking statement*
17	S3: So, is anything attaching other than the water?	*Clarification seeking statement*
18	S2: The Na goes with the hydrogen and the Cl goes to the oxygen.	*Follow-up response – clarifies previous statement*
19	S4: It does? Okay.	*Confirmation seeking & acknowledgement statements*
20	S1: Is it negatives to positives then?	*Consensus checking statement*
21	S2: For instance, this group [using models], see how the Cl is connected to the hydrogen?	*Follow-up response – attempts to clarify previous statement*

In this exchange, the students were relying on the magnetic properties embedded in the 3D models to construct chemical explanations that accounts for what happens after the mixing processes. While manipulating the models, *S4* asks "are the Na and Cl connected to the hydrogen or to the …?" (LN 16). Here, the student equates magnetic attraction to chemical connectivity, an unintended consequence. *S2*, in a follow-up response in line 18, erroneously says "the Na goes with the hydrogen and the Cl goes to the oxygen." *S4* acknowledges this follow-up response, skeptically, in line 19 "it does? Okay." *S1* then asks "is it negatives to positives then?" highlighting how the students were using the 3D models to explain the molecular events involved in the dissolution process. More importantly, the exchanges in Table 3 provide empirical evidence that modeling prompted discourse that allowed the students to develop joint understanding of the dissolution process. This claim is based on the observation that student engagement during modeling was characterized by statement types indicative of group negotiation of meaning making processes. This includes clarification and consensus checking statements (see LN 16, 17, 19-20), confirmatory and acknowledgement statements (LN 19), follow-up responses to other member's statements (LN 18, 21) and information sharing moves (LN 15).

A second episode from Group B is shown in Table 4. This episode further highlights the finding that modeling prompted discourse characterized by group negotiation of meaning making processes. That is, students' dialog about hydration processes, the spacing between water and dissolved NaCl, and the connectivity of atoms in ionic vs. covalent bonds indicated social negotiations about the dissolution process of ionic solids in water.

Table 4 Continuation of Group B's dialog on drawing "after mixing" particulate diagrams

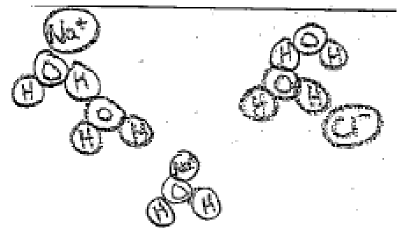
	Dialog	Commentary
22	S1: I'm just doing the water molecule and then a Cl attached to one of the H's and leaving space between it. Then I'm doing another one with the Na attached to the O. You just have to make sure there's the same amount of Cl's and Na's.	*Modeling activity; information sharing statement*
23	S3: They would be touching then? Well, they're all ionic bonds, right?	*Clarification seeking & consensus checking statements*

24	S4: They would touch because they're ionic. The water molecule should actually overlap a little	*Acknowledgement & clarification statements*
25	S3: The water should overlap because they're covalent?	*Consensus checking statement*
26	S4: Yeah	*Acknowledgement statement*
27	S1: What part? The Cl went to the oxygen?	*Clarification seeking move*
28	S2: No, the Cl went to the hydrogen.	*Follow-up response – clarify previous statement*
29	S3: So, you're just drawing different ones?	*Consensus checking statement*
30	S4: Yeah, and I'm doing some that are just water molecules and then I'm doing some that are water molecules with the Cl or Na attached to them.	*Acknowledgement & information sharing statement*

Throughout the exchange shown in Table 4, modeling and group negotiation of what is connected to what or how to space ions in water were characteristic features of the students' discourse. For instance, *S1* proposed showing the after mix process by drawing "the water molecule and then a Cl attached to one of the H's and leaving space between it" (LN 22) and repeating the same process for Na. *S1* further suggest to make sure "there's the same amount of Cl's and Na's" (LN 22), to which *S3* responds to with a clarification seeking question – "They would be touching then?" (LN 23). We believe the use of "touching" in this case arises from a limitation of the model – the use of magnets in the models. While *S1* was proposing separating the Na and Cl and hydrating them with water molecules, *S3* assumed they will be touching because "they are all ionic bonds" (LN 23). Characteristic of group negotiation of meaning making processes, *S3* follows his response with a consensus checking statement, "right?" (LN 23). Thus, throughout their dialog, the students invoke the chemical ideas of ionic bonding, covalent bonding, and refer to the model to make sense of what is connected to what. Their entire dialog is characterized by clarification seeking moves, consensus checking statements, acknowledgements, and information sharing moves all in the context of the models.

Following their dialog in Table 4, members of Group B continued to revise their particulate drawing. Their final dialog, an extended exchange between *S3* and *S2*, is shown in Figure 3 along with their final "after mixing" particulate drawing.

	Dialog	**Commentary**
31	S3: So then there should be a gap between the ions?	*Consensus checking statement*
32	S2: Yeah, but I wouldn't necessarily show any NaCl together because if we had enough water they'd all be separated	*Acknowledgement and follow-up response*
33	S3: They'd all be separated? Okay.	*Confirmatory statement*
34	S2: So, I'd show just the Cl and one with just the Na.	*Follow-up response*
35	S3: Okay, so I'll start with a water molecule and then I can put a Na+ attached to that one. Should I show the water connected to each other then?	*Consensus checking statement and group's final drawing*



36	S2: Yeah, if you want.	*Acknowledgement statement*

Fig. 3 Sociochemical dialog involving course instructor and Group B and the group's "after mixing" particulate drawings of NaCl and Water

As shown in Figure 3, Group B's final particulate drawing shows a sodium ion attracted to the O of water and separately a chloride ion attracted to the H of water. In addition to the separated ions, the students show water molecules that are attached to each other. Similar to their previous dialog, this final episode was mainly characterized by consensus checking, confirmatory, and acknowledgement statements. This is expected given that the group was finalizing their final particulate drawings of the dissolution process.

Discourse on Symbolic Representations of Dissolution Processes – The Case of Group C

The third case we present comes from Group C, a group consisting of two females (*S1* and *S3*) and two males (*S2 and S4*). *S1* was the group's facilitator, *S2* the spokesperson, *S3* the recorder, and *S4* the group's process analyst/skeptic. We selected this group to illustrate how the use of 3D models dissuaded students from selecting incorrect symbolic equations representing the dissolution process. Table 5 shows the group's sociochemical dialog, the multiple-choice options they were selecting from, and accompanying instructions for solving the problem. The distractors in the multiple-choice options (a, b, d, and e) were common student misconceptions about the dissolution process of ionic solids in water reported in the science education literature (e.g., Nyachwaya et al. 2011; Naah and Sanger 2012). Option B shows the misconception that ionic solids react with water to form an acid (HCl) and base (Na_2O) (Ebenezer 2001; Naah and Sanger 2012; Tien et al. 2007). Option A shows the misconception that ionic solids dissociate as neutral atoms (Kelly and Jones 2007; Naah and Sanger 2012; Smith and Metz 1996). Options D and E show common student errors related to charge-subscript use (D) or state phases (E), both reported in the literature (e.g., Nyachwaya et al. 2011; Kelly and Jones 2007; Liu and Lesniak 2006; Naah and Sanger 2013). Of these, the misconception in option B is often the most prevalent among chemistry students (Kelly and Jones. 2007; Naah and Sanger, 2013).

Table 5 Group C's dialog on selecting symbolic equations to represent NaCl dissolution

Directions: 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)*

	Dialog	Commentary
37	S1: What equation do you think it is?	*Information seeking statement*
38	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	*Follow-up response. S4 uses chemical justification as to why B is correct*
39	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 …	*Challenge statement: S3 challenges the claim made by S4*
40	S1: It really [*water in the model*] doesn't break apart	*Support statement*
41	S2: It just bonds	*Response statement*

As can be seen in the dialog in Table 5, students were inclined initially to select option B. This was mainly induced by the surface information present in the given equation (the presence of H_2O in the equation) and preceding student acts – the fact that the students macroscopically mixed water and NaCl. Hence, *S4*'s comment that "B is the only one that makes sense because it's the only one adding the water" (LN 40). However, modeling with the 3D magnetic models also prompted discourse that eventually dissuaded the group from selecting this common misconception. This is illustrated by *S3*'s comment that "but it has HCl and the Na is with the O. This [points to Na^+] won't connect to the negative [pointing to O] since it's extra …" (LN 41). Here, the magnets embedded in the models are helping *S3* mimic the positive and negative charges in ionic centers. Similarly *S1* noted that water in the model "really doesn't break apart" (LN 42). The comments from *S2* and *S4* suggest these students were not completely satisfied with the arguments put forth by their peers. This highlights an important feature of the students' engagement during modeling: student discussions during modeling tended to be dynamic and highly interactive, with all voices participating in the negotiation process.

The voice of the course instructor was similarly present during the sociochemical dialog related to the symbolic representation of the dissolution process. The instructor, in this case, was using the models to dissuade the students from selecting misconceptions such as the formation of acid-base species when salts are dissolved in water. Consider, for example, the dialog in Table 6 below in which the course instructor used modeling to dissuade members of Group C from selecting option B.

Table 6 Student-teacher dialog involving Group C and their selection of symbolic equations to represent dissolution of NaCl in water

Dialog	Commentary

42	T: Did you observe this? Did you see the Na bonding to oxygen and a Cl bonding to an H?	*Teacher move refers to model – did the students observe this with the models*
43	S1: No, we saw the water stay together	*Model-based response*
44	T: The water stayed together. So, does B support that?	*Confirms group observation, guides them away from B*
45	S1: No, it's saying that it all breaks up	*Again, model-based response*
46	T: B does?	*Follow-up response*
47	S1: That's what it's saying	*Follow-up response*
48	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?	*Teacher uses modeling to facilitate student understanding*
49	Group: No	
50	T: Oh! Okay. So maybe B isn't supported by that. Think about that one a little bit more	*Suggest to students option B is not supported by observed evidence*
51	S4: C then? She was talking about the charges	*Evidence for changed understanding*
52	S3: That's what I was going to say. It doesn't change its composition when you mixed it.	*Model-based reasoning*

The instructor's initiating move in line 42 asked the students if they observed what the chemical equation in option B was showing with the model kits – the formation of a bond between sodium and oxygen and between hydrogen and chlorine (LN 42). With this move, the instructor was using the models to connect particulate observations of the dissolution process to the symbolic equation in option B. Her question of "did you observe this?" suggests implicitly that the combination of Na with O and H with Cl does not meet the standard of what count as chemically justified and acceptable representation of dissolved ionic solids. Member *S1* responded to the teacher's inquiries by saying "No, we saw the water stay together" (LN 43). When saying "the water stayed together," the students and the instructor are referring to the 3D models of water. The instructor responded to *S1* by confirming the students' response and validating the students' model-based observation – "the water stayed together" (LN 44). She followed up this response with another move that referred to the model and attempted to link their observation with the modeling activity – "So, does B support that?" (LN 44). She further comments what option 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 48) and then asks the students if they observed this during modeling – "Is that what you observed? Did the O's and H's ever break apart?"(LN 48). The group responded by saying "No" and the instructor acknowledged this and hinted that may be the students should entertain another option – "So maybe B isn't supported by that. Think about that one a little bit more" (LN 50). The instructor used modeling to communicate to the students what counts as appropriate symbolic representations of dissolved ionic solids in water and invoked modeling to co-construct chemical explanations with the students.

Discussion

In this study we set forth to characterize the nature of classroom discourse prompted by modeling activities (research question 1) and the impact the use of 3D models had on student understanding of the dissolution process of ionic solids in water (research question 2). The results described above show students engaged in collaborative discourse prompted by modeling while also influencing their conceptions of solution chemistry. In this section we describe the patterns of student discourse we observed across all three cases and the role the 3D magnetic models played in enhancing or constraining student thinking and reasoning during modeling. The first sub-section, "characteristic features of student engagement during modeling," addresses the first research question: What is the nature of classroom discourse prompted by the use of physical 3D magnetic molecular models representing the dissolution of ionic solids in water? The second subsection, 'the role of 3D physical models in science teaching and learning,' addresses the second research question: What impact did the use of 3D magnetic models have on students' understanding of the process of dissolving ionic solids in water?

Characteristic Features of Student Engagement during Modeling

Cross case analysis suggested modeling prompted similar discourses within the individual cases. That is, in all three cases the students were thinking about particulate-level explanations for macroscopically observed chemical phenomena (teacher demonstration of dissolving sodium chloride in water in front of class). For example, Group A made particulate-level claims about the relative size of chloride and sodium ions (Table 1) and went on to generate particulate diagrams that reflected appropriately scaled atomic and ionic sizes (Figure 2). The students also paid attention to how the 3D models represented ionic compounds (NaCl) vs. molecular compounds (H_2O): solid NaCl was shown as a lattice ionic species adjacent to each other whereas the atoms of water molecules were shown as covalently attached and though they were overlapping (see Figure 2). Group B similarly made particulate-level claims about the connectivity and spacing of atoms and ions in solution (Table 2). Their final particulate drawing of NaCl dissolved in water considered ideas featured in the group's discourse. This included references to atomic and ionic connectivity after dissolution (lines 16-18, 21, Table 2; lines 27-28, Table 3), ionic bonding versus molecular bonding (lines 23-27, Table 3), and gaps between the Na and Cl ions (lines 33-35, 37, Figure 3).

A comparison of word clouds (Ramlo, 2011) for Group A and Group B's sociochemical dialogs from the results section with the open-software *Wordle* (Feinberg, 2013; McNaught and Lam, 2010; Ramlo, 2011) indicated that the most frequent words in the group's dialogs referred to particulate-level explanations (see Figure 4). As shown in Figure 4, the symbols Na and Cl, water, attachment (attach or attached), molecule(s), and hydrogen were most prominent in Group B's dialog. Consistent with their results in Tables 3, 4 and Figure 3, these are words associated with the group's discourse on the connectivity of atoms, spacing between ions, and representation of atoms and ions at the particulate level. However, we caution that while the words 'water,' 'hydrogen,' and the symbols Na and Cl might refer to entities at the particulate level, these are words that can also be used to bridge between the macroscopic and the particulate levels of description (see Taber, 2013). In the context used in the present study, we suspect the students were referring to particulate level descriptions but we have no hard evidence to conclude that was the case. For Group A, the most prominent words in their dialog were the symbols Na and Cl , big (big or bigger), ions, four [in reference to the number of sodium and chloride ions present in the models], and draw. This is similarly consistent with their discussion of the size of atoms and ions and how to draw particulate diagrams of the dissolution process (Tables 2 and 3, Figure 2). It is clear that modeling induced references to particulate-level explanations in both groups.

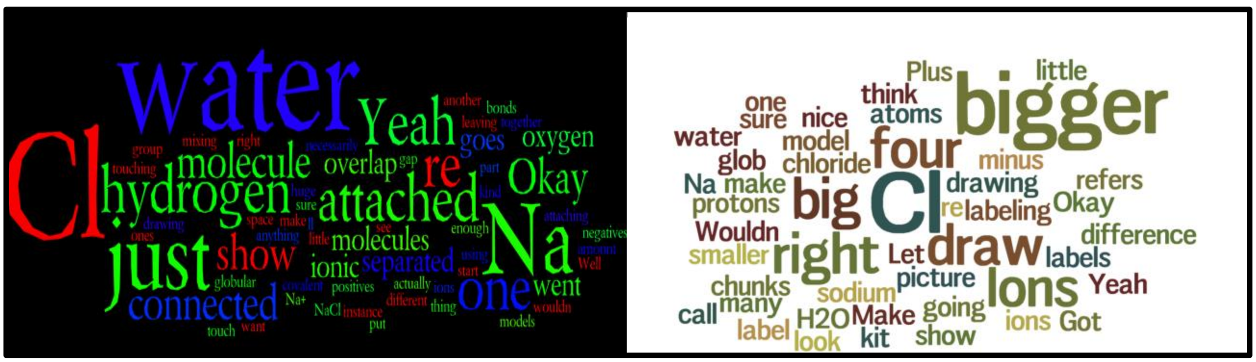


Fig. 4 A comparison of word clouds for Group B (left figure, black background) and Group A (right figure, open-background) dialogs, as presented in the results section, highlights the most prominent words in their dialogs

The codes in columns in the data tables (Tables 2-5) characterize the nature of student statements during their sociochemical dialogs. These include clarification statements posed to the group, confirmatory response statements, consensus checking statements, and acknowledgement statements. The nature of these statement types suggests the groups were involved in the collective development of chemical justifications to explain the dissolution process of NaCl in water. This collective co-construction of chemical explanations was model-driven. That is, modeling induced discourse practices that impacted students' decision making process of what are appropriate representations of the dissolution process and how to communicate that in writing via particulate diagrams and symbolic equations. This characteristic feature of student engagement during modeling bodes well for recent calls in national science standards documents to engage students in the development and use of models, construction of explanations and engaging arguments from evidence (NRC, 2011, 2013). The manipulative nature of the 3D models used in this study induced sociochemical dialogs that were rich with particulate-level language and engaged the students in the process of co-constructing chemical explanations.

The Role of 3D Physical Magnetic Models in Science Teaching and Learning

Much of the discourse described in this paper resulted from the use of 3D models. For instance, the student reasoning and claims about the size of atoms and ions described above was prompted by modeling. Previous studies found student difficulties with representations of the size of atoms and ions (*e.g.*, Nyachwaya et al. 2011; Coll and Treagust 2003). For example, Nyachwaya et al. (2011) reported that students in their study "explicitly represented hydrogen atoms as bigger than oxygen atoms within water molecules" (p. 17) whereas students tended to show calcium and chloride ions in calcium chloride ($CaCl_2$) "to be of the same size" (p. 17). Overall, Nyachwaya et al (2011) reported that 21% of students in their study provided drawings with problems on how they represented the sizes of atoms and ions. As can be seen in Figure 2, the use of the 3D models in this study allowed students to draw appropriate representations of atomic sizes and ions – when drawn to scale, the hydrogen atoms are much smaller than oxygen atoms within the water molecules and sodium ion is much smaller than chloride ion in sodium chloride. Discussion of these ideas was also featured in student discourses. Thus, 3D modeling, in this instance, allowed students to generate appropriate particulate representations of ionic and molecular compounds, highlighting how magnetic models can transform science teaching and learning.

There were some limitations apparent in the use of the 3D magnetic magentic models to teach solution chemistry. The most glaring limitation was the students' tendency to equate attraction between magnets as covalent bonding. For example, in Table 4, S2 referred to the attraction between sodium and chloride ions and water as "just bonding." In numerous other instances, students use "attachment" as opposed to "attraction" to describe the interaction of sodium chloride and water. In the chemical education literature, there is a common student alternative conception (misconception) that chemical bonding is something different from and more than just attractions (see Taber, 1998), leading to interactions such as solvation not seen as bonding. Here the students seem to recognize the solvation as a bonding effect, albeit one that is covalent in nature as supposed to ion-dipole interaction. It is thus possible that the 3D models were introducing new set of misconceptions about bonding and connectivity while dispelling other common misconceptions. Part of this limitation arises from student inability to distinguish models from reality. Harrison and Treagust (2002), for instance, describe how learners interpret models as exact replicas of reality. A second limitation is getting to a complete hydration of each ion, as would take place in a dissolved salt solution. The sodium and chloride ions sometimes migrate back together even with mixing of the magnetic balls. The instructor wanted to include a small salt matrix to emphasize solid salt structure, but decided to limit the water molecules to minimize cost and sample size. The teacher tried to address this limitation by emphasizing in the macroscopic demonstration prior to the activity that adding some water to a pile of salt dissolves some of the salt. More water could be added to get more of the salt to dissolve. This point was used again during a whole class discussion after the modeling activity to help connect the macroscopic observation with this particulate level modeling activity and the limitation of not quite getting to complete solvation of all of the ions. Consequently, instruction and facilitation accompanying 3D modeling need to explicitly address the limitations of the model and its intended purposes.

Representations of the Solvation Process

One finding in the study is worth noting. Student drawings show the ions each only bonded to a single water molecule through one solvent molecule-solute ion interaction. All the groups consistently showed hydration of sodium chloride this way. This representation is inconsistent with the scientifically accepted model of solvent sheaths effectively surrounding each solute ion. There are two possible hypotheses to account for this finding. The first is that this is due to a limitation of the magnetic models. That is, although each ion model had six magnets embedded in them to mimic the 6:6 coordination in the sodium chloride crystal formation (3D Molecular Design, 2013), it is possible that the students did not recognize these sites become available for water molecules upon the dissolution of the crystal salts. Also, since this was early on in the general chemistry course, students had not covered ‘solvation’, which comes several chapters later in ‘intermolecular forces’. We however believe that with this activity, a background has been laid to bring up the idea when we talk about intermolecular forces. Again, either in whole class discussions or through individual group discussions depending on the timing of the session, the instructor demonstrated a fully solvated ion with six waters attracted to the ion. Often groups would naturally build a fully solvated ion as they manipulated the magnets. They did however not always draw this, perhaps due to the complexity of drawing a fully solvated ion.

But there is alternative possibility that we strongly suspect accounts for the observed behavior. There is a common student misconception reported in the chemistry education literature whereby students assume, in regards to ionic structures, that an ion with a single charge (i.e., sodium ion) can only bond to one counter ion (Taber, 1994, 1997; Taber, Tsaparlis & Nakiboglu, 2012). It is therefore possible that by representing ionic salts through one solvent molecule-solvent ion interaction, the students are using the valency conjecture (Taber, 1994, 1997) and transferring an alternative conception normally linked to the solid state to their understanding of the solution process. We don't have hard evidence to conclude this based on the present data but intend to examine this hypothesis in future studies.

Conclusions

Student groups in this study used the 3D magnetic models to generate final particulate drawings of dissolution processes that were deemed to be appropriate representations of what happens to dissolved ionic solids at the atomic/molecular level. Similarly, model-initiated discourse dissuaded students from selecting misconception items used as distractors in multiple choice symbolic equations representing the dissolution process. That groups co-constructed a final appropriate particulate representation of dissolution processes is not of itself a novel finding; multiple studies in physics education have shown how the final solution of physics problems in cooperative groups is often superior to the solution produced by students working on the same problems individually (e.g. Heller and Hollabaugh 1992; Tobin, et al. 1994). What is particularly interesting is the nature of collaborative discourses prompted by modeling with the 3D models. That is, our findings suggest modeling using the 3D magnetic models facilitated students' co-construction of what is an appropriate chemical representation of the dissolution process. This is important for two reasons. First, numerous studies found student difficulties related to the representation of chemical ideas (see Abraham et al. 1994; Becker, et al. 2013; Calyk, et al. 2005; Cooper, et al. 2010). The finding that collaborative discourse led student groups to better represent a chemical phenomenon (i.e. dissolution processes) at the particulate-level is thus encouraging. More importantly, the identification of the characteristic features in the students' dialog that aided their co-construction of chemical explanations with respect to the dissolution process has implications for curriculum design efforts.

Secondly, the use of the 3D models appears to have eliminated certain shortcomings associated with the use multimedia and computer animations as instructional interventions for teaching solution chemistry (Ebenezer 2001; Kelly and Jones 2008; Naah and Sanger 2013). This includes the inability to feel intermolecular forces, mimic hydration processes, or tangible ways of experiencing the polar nature of water molecules in dissolution processes. This was not an issue in this study as students were able to "feel" the forces between the molecules through touch-sensory feedback mechanism and the magnetic properties allowed them to model molecular polarity. The use of the

3D models particularly limited the amount of extraneous information that could distract students during modeling. Naah and Sanger (2013) and Kelly and Jones (2008) have commented on how animations of dissolution processes can be distracting for students. Naah and Sanger (2013) went as far as arguing "animated motions in depiction of chemical reactions do not necessarily lead to better learning" (p. 111) and further warning chemical educators that "instructors should carefully consider the instructional effectiveness of any animations before selecting it for classroom use" (p. 111). The use of 3D models appears to alleviate some of the concerns raised by these authors.

The finding that collaborative discourse was a critical feature of the students' engagement during modeling is important. These class discourses can shape how models are used, how they can contribute to the social construction of knowledge, and how they are interconnected with students' other meaning-making mechanisms. Wu (2003) points out that "community members create particular ways of talking, thinking, and interacting, which shape and are shaped by the communicative processes of class discourse" (p. 873). We illustrated here the various ways in which the use of 3D models prompted discourse that led to model-based reasoning about the dissolution process and how this discourse shaped how this particular class was using models.

Limitations of the Study

This study had some inherent limitations due to its design. While the large number of student participants and multiple cases gives us confidence about the generalizability of the findings, it is worth noting that the findings are from a single class with one instructor. Multiple studies have shown the way teachers facilitate classroom discourse affects the nature of students' discursive practices (Becker, et al. 2013; Berland 2011; Warfa et al. 2014). Thus, we do not claim generalizability of the student-teacher dialogs to other contexts or classrooms. It would be interesting to see how other instructors use these models to facilitate student learning in a cooperative setting. Similarly, while we feel confident about the nature of the discourse prompted by the models during the small group interactions, we do note this too was contextualized to the specific topic of solution chemistry. The findings therefore do not present a generalizable view of model-initiated discourses across all chemistry contexts. In the future, we plan to investigate the nature of students' engagement during modeling in contexts other than solution chemistry.

Implications for Teaching and Learning

Our analysis of classroom discourse practices suggests the need for a unified approach to modeling instruction in which modeling activities are coupled to the social and interactional nature of science classrooms. That is, while individual modeling activities with new technologies can lead to enhanced student understanding (Bivall, et al.

2011; Khan 2011), we suggest engaging students in collaborative discourse during modeling may provide a better mechanism for constructing scientific explanations. As we have shown in this paper, student groups were involved in the collective development of chemical explanations based on observations they made by modeling the dissolution process. This collective development of ideas allowed individual students to confirm each other's understandings, seek group consensus of what the models were showing, and acknowledge each other's positions. Thus, model-based reasoning on what counts as appropriate representation of chemical ideas was socially negotiated through group dialogs. We therefore contend that the way scientific explanations are constructed during modeling in large part depends on how students negotiate about the meaning of scientific ideas. This also has implications for how teachers facilitate student learning with models, a subject we consider in a future manuscript.

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