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ADAPTING A METHODOLOGY FROM MATHEMATICS EDUCATION RESEARCH TO CHEMISTRY EDUCATION RESEARCH: DOCUMENTING COLLECTIVE ACTIVITY

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ABSTRACT. In this report, we adapt and extend a methodology for documenting the collective production of meaning in a classroom community. A cornerstone of the methodological approach that we develop is a close examination of classroom discourse. Our efforts to analyze the collective production of meaning by examining classroom interaction are compatible with the relatively recent emphasis in mathematics and science education research that focuses on how communities of learners establish ideas through discourse and inquiry. The methodological approach we take builds on and extends an approach from mathematics education that uses Toulmin's argumentation model to document and analyze students' conceptual progress. Our modification introduces a new criterion for empirically demonstrating when particular ways of reasoning become part of the normative practices of the community. An example from an undergraduate course in physical chemistry is used to illustrate the methodology.

KEY WORDS: classroom practice, collective activity, discourse, methodology, undergraduate chemistry, undergraduate mathematics

In this report, we adapt and extend a methodology for documenting the collective production of meaning in a classroom community. The methodological approach we develop is the result of a synergy between undergraduate chemistry and mathematics education researchers. This synergy built on the experience of the mathematics education researchers in using Toulmin's (1969) model to study classroom discourse and the complementary experience of the chemistry education researchers in studying student learning in innovative classrooms. The result was the adaption of a methodological approach developed by the mathematics education researchers to document collective progress in inquiry-oriented classrooms. Our efforts to analyze students' ways of reasoning by examining classroom interaction are compatible with the relatively recent emphasis of mathematics and science education research that focuses on the collective activity by which communities of learners jointly build ideas (Hershkowitz, Hadas, Dreyfus & Schwarz, 2007;

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Rasmussen, Zandieh & Wawro, 2009; Saxe, Gearhart, Shaughnessy, Earnest, Cremer, Sitabkhan et al., 2009).

The collective activity of a chemistry or mathematics class refers to the normative ways of reasoning that develop as students work together to solve problems, explain their thinking, represent their ideas, etc. These normative ways of reasoning, also known as a classroom mathematical practice (Cobb, Stephan, McClain & Gravemeijer, 2001) or, in our case, a classroom chemistry practice, can be used to describe the mathematical or scientific activity of the classroom and may or may not be appropriate descriptions of the characteristics of each individual student in the class. This last point is critical to the notion of collective activity. It offers a perspective of the social context of the classroom that affords students *opportunities* for conceptual growth. The notion of collective activity also resonates with how instructors typically think about their students when they are teaching. For example, in a class of 40 students, instructors often make decisions based on their sense of the class as a whole while recognizing that there are individual differences (Cobb & Yackel, 1996; Phillips, 2003). As such, the theoretical notion of a classroom practice (whether it be a classroom mathematical practice or a classroom chemistry practice) is one that has strong pragmatic connections.

One promising method for analyzing classroom practices, which was originally developed in mathematics courses, uses a three-phase approach grounded in Toulmin's (1969) argumentation scheme (Rasmussen & Stephan, 2008). This method for documenting the collective production of meaning provides an empirical basis for examining the quality of classroom discourse, for reflecting on instructional design, and for comparing learning opportunities across classrooms. Adapting and extending this method to inquiry-oriented chemistry classrooms provides a unique opportunity to modify the method as needed to fit a new content domain and to investigate how students develop understanding of ideas and symbolism in physical chemistry.

Active Learning in Physical Chemistry Classrooms

The use of Toulmin's model to document collective production of meaning requires a classroom that involves active student participation and discussion. The process-oriented guided inquiry learning (POGIL) instructional approach typically creates such classrooms.

Since its inception in 2003, the POGIL project has developed and disseminated curricular materials that promote active learning based on a social constructivist approach (Spencer & Moog, 2008). In recent years, numerous articles have been published in the literature describing the POGIL approach (Farrell, Moog & Spencer, 1999; Hanson & Wolfskill, 1998; Spencer, 1999) and its positive impact on student performance in a variety of institutional contexts (e.g., Lewis & Lewis, 2005).

POGIL implementations are oriented toward small group discussion in which students work in teams of three to five on materials that provide contexts and prompts to analyze data and explain concepts. The POGIL materials for physical chemistry courses were designed to promote discussion of concepts and verbalization of understanding, in addition to developing facility with derivations, manipulations, and interpretations of equations. For example, in the thermodynamics activities, students are asked to "Describe the meaning of Eq. 1 $[G \equiv U + PV - TS]$ using grammatically correct English sentences" and to "Use a grammatically correct English sentence to explain the meaning of the derivative …" (Spencer, Moog & Farrell, 2004). Thus, the students are prompted to discuss and negotiate the meaning of the mathematical equations and concepts under study.

The instructor facilitates student learning by appropriately guiding and questioning the teams as they work through the specially designed activities. Most of the student discussion takes place in the small groups with periodic reporting out via whole class discussion, which allows for a review of student responses and subsequent elaboration of concepts. Having students work in groups and engage in interactive whole class discussion is a pedagogical strategy that has its roots in a variety of social constructivist theories (e.g., Lave, 1988; Vygotsky, 1978). These social theories of learning offer a lens through which to view and explain how learning takes place via the collective activity of the classroom. This report contributes to a methodology for documenting students' learning as they engage in such collective activities.

Toulmin Analysis in Science and Mathematics Education

The methodological approach we take builds on and extends the approach detailed by Rasmussen & Stephan (2008) for using Toulmin's argumentation scheme as a way to document and analyze students' mathematical progress as it occurs in inquiry-oriented classrooms. These inquiry-oriented classrooms had whole class discussions in which instructors routinely inquired into how their students were thinking and where students routinely inquired into challenging problems. Student inquiry involves explaining and presenting one's reasoning, as well as attending to, questioning, and commenting on the reasoning of others. Such classrooms are beneficial for researchers as they allow one to trace the growth of ideas as they are initiated and constituted via classroom discussion and argumentation. Such classrooms are beneficial for learners as there is mounting evidence that discussion and argumentation improves students' conceptual understandings (e.g., Asterhan & Schwarz, 2007; Sampson & Clark, 2009; Osborne, 2010; Rasmussen, Kwon, Allen, Marrongelle & Burtch, 2006; Zohar & Nemet, 2002).

In his seminal work, Toulmin (1969) created a model to describe the structure and function of argumentation. Figure 1 illustrates that for Toulmin, the core of an argument consists of three parts: the data, the claim, and the warrant. In an argument, the speaker makes a *claim* and presents evidence or data to support that claim. Typically, the *data* consist of facts or procedures that lead to the conclusion that

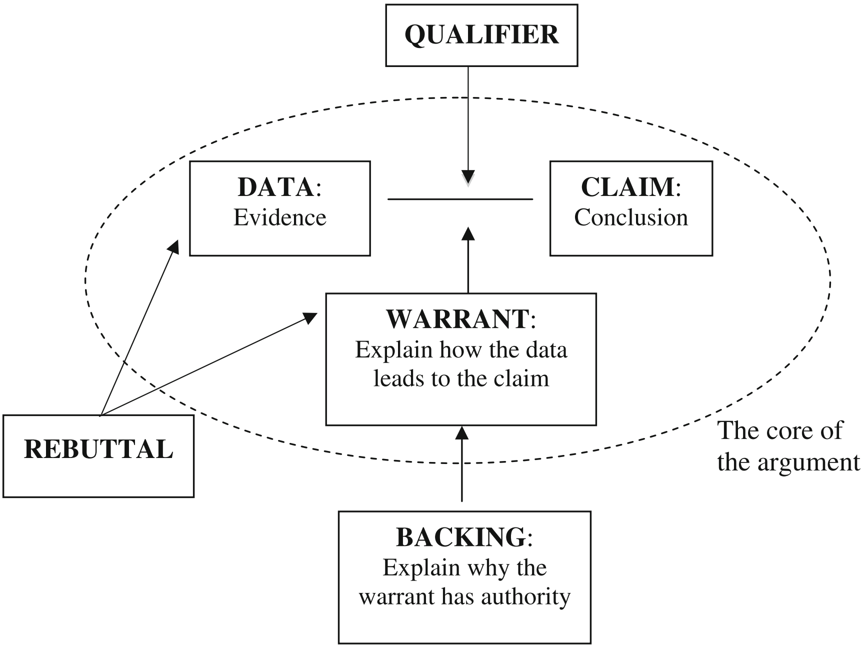

Figure 1. Toulmin's model of argumentation

is made. To further improve the strength of the argument, speakers often provide more clarification that connects the data to the claim, which serves as a *warrant*, or a connector between the two. It is not uncommon, however, for *rebuttals* or *qualifiers* to arise once a claim, data, and warrant have been presented. Rebuttals and the qualifiers aid to propel the argument forward. If one disagrees with the claim, he or she may present a rebuttal, or a counterargument that shows disagreement. When this type of challenge is made, often a qualifier is provided, which is a way to provide specific conditions in which the claim is true. Finally, the argumentation may also include a *backing*, which demonstrates why the warrant has authority to support the data–claim pair. Genuine argumentation therefore occurs when students are involved in turn-taking or cycles of conversation where each person attempts to interpret the meaning of another's statement and adjusts his or her response. Finally, it is important to note that the elements of Toulmin's model do not follow a specific order of occurrence.

The Toulmin model of argumentation has been adapted by many in the fields of mathematics and science education as a tool to assess the quality or structure of a specific mathematical or scientific argument and to analyze students' evolving conceptions by documenting their collective argumentation (Erduran, Simon & Osborne, 2004; Inglis, Mejia-Ramos & Simpson, 2007; Krummheuer, 1995; Weber, Maher, Powell & Lee, 2008; Yackel, 2001). For example, Weber et al., (2008), through analyzing the evolving argumentation of students making and defending decisions about buying dice, illustrated specific ways in which discussion can contribute to learning and offered descriptions of social and environmental conditions that invite productive argumentation. Krummheuer (1995) noted that argumentation is typically accomplished through the direct interaction of several participants rather than through a monologue offered by one member of the classroom. Consistent with this perspective, Yackel (2001) stated that "what constitutes data, warrants, and backing is not predetermined but is negotiated by the participants as they interact" (p. 7), highlighting that the particular statements that students use in arguments are situation-specific, emergent, and co-constituted.

Adapting a Methodology for Documenting Collective Activity

The setting for this study is a physical chemistry classroom at a regional comprehensive university in the Midwestern United States. Ten female and five male students were enrolled in the course. These students were all junior or senior B.A. or B.S. Chemistry majors, with one student pursuing a double major in mathematics. One student had not taken calculus, while the rest of the students had taken one or two semesters of calculus. The class met for 50 min, 3 days per week. The course was taught using the previously described POGIL instructional approach and materials (Spencer et al., 2004). The 15 students were assigned to four groups, which remained stable for the sessions described in this study. Students typically spent one third to one half of the class time working in their small groups, while the rest of the class time was spent in whole class discussion. Table 1 provides a list of the topics covered and the number of class sessions for each topic during the data collection period.

Data for this report were drawn from classroom video recordings from a one semester undergraduate POGIL physical chemistry class. From this larger data set, we chose to focus on a 5-week unit on thermodynamics. We chose this unit because it contained a rich interplay between mathematical symbolism and abstract concepts. This interplay between mathematical symbolism and abstract ideas in physical chemistry drew on the strengths of the interdisciplinary research team and represented a particularly challenging terrain for students. The goals of our analysis were to document the collective ways of reasoning that emerged in this classroom and explore how

TABLE 1

Outline of class coverage of concepts

Date	*Content*
2/2	Work
2/4	First law of thermodynamics
2/6	Enthalpy
2/9	Enthalpy
2/11	Heat Capacity
2/13	Heat capacity; temperature dependence of the enthalpy of reaction
2/16	Temperature dependence of the enthalpy of reaction; entropy
2/18	Enthalpy change as a function of temperature
2/20	Third law of thermodynamics
2/23	Third law; Gibbs and Helmholtz energy
2/25	Gibbs and Helmholtz energy
3/2	Gibbs energy as a function of temp and pressure

Toulmin's scheme could be used as a methodological tool to document these collective ways of reasoning.

To address these goals, we began by examining the discourse patterns using the Toulmin scheme approach detailed by Rasmussen & Stephan (2008). Following this approach, we first created transcripts of every whole class discussion. Next, Toulmin's model was used to create a sequence of argumentation schemes for all whole class discussion for each day, resulting in a comprehensive argumentation log across all whole class discussions. The next phase of the analysis involved taking the argumentation log as data itself and looking across all class sessions to see what scientific or mathematical ideas expressed in the arguments became part of the classroom community's normative ways of reasoning—that is, to determine what ways of reasoning functioned as if shared.

Rasmussen and Stephan found, in the context of the inquiry-oriented mathematics classrooms they studied, that the following two criteria could be used to empirically determine when an idea functions as if shared:

Criterion 1	When the backings and/or warrants for particular claim initially are present but then drop off or
Criterion 2	When any of the four parts of an argument (the data, warrant, claim, or backing) shifts position within subsequent arguments.

These specific ideas that function as if shared are then organized around a particular theme in order to indicate the common thread among the related ideas. This common theme is what is called a *classroom mathematical practice*. Taken together, these classroom mathematical practices constitute the collective mathematical growth of the classroom community. For example, in a differential equations classroom, Stephan & Rasmussen (2002) documented the emergence of six different classroom mathematical practices. One particular classroom mathematical practice is referred to as, "Creating and organizing collections of solution functions." This particular practice consists of the following four normative ways of reasoning: (a) The graphs of solution functions do not touch or cross each other; (b) Two graphs of solution functions are horizontal shifts of each other for autonomous differential equations; (c) Solution functions can be organized with different inscriptions such as phase lines, time graphs, and rate of change graphs; and (d) Phase line signify the result of structuring a space of solution functions.

While the two criteria were clearly defined, our research team had limited success in utilizing them to determine when specific ideas function as if shared in the particular POGIL classroom we were studying because this classroom had qualitatively different whole class discussions compared to the whole class discussions reported in Stephan & Rasmussen (2002). Specifically, in the differential equations classroom, whole class discussions were typically occasions during which mathematical ideas and various interpretations were debated and further developed. In comparison, the whole class discussions in the POGIL classroom were typically occasions for students to report back on their conclusions from small group work and to receive confirmation from other groups and the instructor as to whether or not their conclusions were correct.

Creating an Alternative Criterion for Identifying Normative Ways of Reasoning

The difficulty we encountered in utilizing the two criteria led to a central and unexpected methodological finding. We discovered a new, third criterion for determining whether an idea is functioning as if shared. This new criterion, which emerged from analysis of argumentation logs across multiple class sessions, demonstrated that classroom participants repeatedly used specific data or warrants to justify claims and answer questions. Thus, the new criterion we discovered is:

Criterion 3 When a particular idea is repeatedly used as either data or warrant for different claims across multiple days.

In this section, we illustrate how the repeated use of a particular idea can indicate when an idea functions as if shared. In the following examples, the idea of the relative motions of particles in solid, liquid, and gas phases of matter are repeatedly used within the physical chemistry classroom to make claims about chemical properties such as enthalpy and entropy. Specifically, the class uses the ideas that the motion of gas phase particles is unrestricted, in liquids the movement of particles is more constrained, while in the solid phase the motions of particles are limited to vibrations at fixed positions. The relationships between the translational motion of particles in solid, liquid, and gas phases of matter are used as either data or warrants on three different days to support different claims about chemical properties. In the examples that follow, the specific instances in which participants used the motion characteristic of a phase in arguments about physical chemistry concepts have been italicized. The speaker is indicated in parentheses, and direct quotes are quoted.

In a whole class discussion about the standard state entropy values of solids, liquids, and gases, the instructor asked the students which phase of matter would have the most entropy (solids, liquid, or gas). Two argumentation schemes from this discussion are as follows:

Scheme 1	Context of argument: Entropy	Date: 2/16
Claim 1	Solids have the least entropy of solid, liquid, and gas phases of matter. (Multiple students)	
Data 1	"*You can't change the way they are arranged, solid*." (Jane)	

Scheme 2	Context of argument: Entropy	Date: 2/16
Claim	The standard state entropies of liquids will be in between those of solids and liquids (Instructor)	
Data	"*They're moving around a little bit, but not as far as in gases*." (Marie)	
Warrant	"They can't just go moving off, we still have forces and interactions." (Instructor)	

In scheme 1, the class used the motion of solid, liquid, and gas particles to justify claims about entropy of solids. In scheme 2, Marie references that the entropy of solids will be the least because position of the solid particles cannot be changed. The data that liquids move more than solids and less than gases supported the claim that liquids have standard state entropy values between those of gases and solids.

In argumentation scheme 1, the relative motion of solids, liquids, and gases was used to reason about entropy of a substance. Later, these data were used to make claims about other chemical properties. In the following class period, the relative motion of solid, liquid, and gas particles was extended to a discussion of the enthalpy change for the process of melting ice. A critical thinking question in the POGIL workbook asked students to explain why the enthalpy change (ΔH) for the process of evaporating water, H_2O (l)→H_2O (g), is positive. As summarized in the following argumentation scheme, one student, Zane, presented his group's reasoning for the question.

Scheme 3	Context of argument: Enthalpy of a phase change	Date: 2/18
Claim	Enthalpy of reaction is positive for the melting of ice (Textbook and Instructor)	
Data	"*Because it's going from a solid to a liquid*." (Zane)	
Warrant 1	Going from a solid to a liquid requires heat because "it [the solid] breaks down." (Zane)	
Warrant 2	"*We put energy in to go from solid to the liquid so we give the molecules enough energy to move around*." (Instructor)	

Zane used the relative energies of solids and liquids to determine the enthalpy change associated with a phase change. The instructor provided the warrant that linked Zane's data and the claim by indicating that the input of energy would be used to increase the motion of the particles. This warrant again referenced the fact that solid particles are in fixed positions while liquid particles do have translational motion. As in the preceding argumentation schemes (schemes 1 and 2), the fact that liquid particles move more than solid particles serves as support for a claim about a chemical property (e.g., enthalpy).

In the following class period, the class discussed the third law of thermodynamics. Again, the students constructed an argument in which they justified the claim using information about the relative motion of particles in solid substances. The argumentation scheme for this exchange is shown below.

Scheme 4	Context of argument: Third law of thermodynamics	Date: 2/20
Claim	All materials must be solid at absolute zero. (Text)	
Data	"*There is no motion*." (Andrea)	
Warrant 1	"The way it's compact." (Andrea)	
Rebuttal 1	"Ok you're sure dancing around it." (Instructor)	
Warrant 2	"*There's no room to move*." (Andrea)	
Rebuttal 2	"It doesn't have to do with space available." (Instructor)	

Warrant 3	"*The particles move in a crystal structure.*" (Tom)
Rebuttal 3	"No they don't have to, we can have amorphous solids." (Instructor)
Warrant 4	"*You don't have any net translational motion where they're shifting positions.*" (Instructor)

Here, Andrea used the lack of movement of solid particles to support the claim that all materials must be solid at absolute zero. The instructor then pressed the students to provide a warrant that clarified the data, but ultimately provided the warrant herself by specifying that the lack of translational motion of gas phase particles (rather than rotational or vibrational energy) was the relevant feature of the motion of solid particles that relates to the third law of thermodynamics. Again, both the data and the warrant in this argumentation scheme reference the relative motion of solid particles compared to liquid particles.

In the preceding three schemes, the class used relationships of the motion of particles in solid, liquid, and gas phases of matter to reason about entropy, enthalpy, and the third law of thermodynamics during several different class periods. This repeated use of the relative motion of solid, liquid, and gas phases of matter as data or warrants to make claims about chemical properties suggests that these specific ideas had become a part of a normative way of the class's reasoning about physical chemistry concepts and functioned as if shared within the class: the motion of gas phase particles is unrestricted, in liquids the movement of particles is more constrained, while in the solid phase the motions of particles are limited to vibrations at fixed positions. Thus, we suggest that the repeated use of a particular idea may be used to indicate when an idea functions as if shared.

Identifying a Classroom Chemistry Practice

The third phase of the methodology developed by Rasmussen and Stephan was to group specific ideas that function as if shared around a particular theme that indicated a common thread among the related ideas. In our data, and consistent with Rasmussen and Stephan's terminology, this common theme is known as a classroom chemistry practice. Throughout the 5 weeks of this study, the POGIL physical chemistry class repeatedly used particulate-level descriptions of solids, liquids, and gases to discuss, describe, and compare physical properties. The normative ways of reasoning that occurred were: (a) Particles are spaced closest together in solids, intermediate in liquids, and farthest apart in gases. (b) Intermolecular interactions are strongest in solids, weaker in liquids, and are negligible in gases. (c) The motion of gas phase particles in solids is unrestricted, the motion of liquid particles is more constrained, while the motion of particles in the solid phase are limited to vibrations in fixed positions. (d) Particles in gases have more energy than particles in liquids, which have more energy than particles in solids. We refer to the collection of these four normative ways of reasoning as the classroom chemistry practice: "Reasoning using particulate-level descriptions of phases of matter."

The development of this classroom chemistry practice spanned seven class periods with relevant argumentation evidenced in six of those 7 days. The number of arguments in which particulate-level descriptions of phases of matter functioned as data or warrants is summarized in Table 2.

Four of the ten arguments involving particulate-level descriptions of the phases of matter are described below as a method of explaining the emergence of the chemistry classroom practice.

Scheme 5	Context of argument: Enthalpy	Date: 2/6
Claim	H_2O (l)→H_2O (g) is endothermic. (Multiple students)	
Data 1	ΔH_{rxn}=44.01 kJ/mol (Carrie)	
Data 2	"*Because it takes energy to go from water to water vapor*." (Tom)	
Warrant	"*To go from the liquid to the gas, I have to put energy in because the molecules are more excited*." (Instructor)	

In scheme 5, two classmates, Tom and Carrie, provided information that served as evidence for the class's claim that the evaporation of water was endothermic. Carrie presented her group's calculated value for the enthalpy change of the process H_2O(l)→H_2O (g), while Tom provided further evidence that the process would require an input of energy by stating that the phase change would require energy. The instructor linked Tom's data 2 statement that energy would be required to transform liquid water to water vapor to the claim by providing a warrant that referenced the relative energy levels of gases and liquids.

Several class periods later, particulate-level descriptions of the phases of matter were again used to reason about the relative entropies of solids,

TABLE 2

The number of arguments involving characteristics of phase by date and topic

Date	*Topic*	*No. of arguments involving characteristics of phase*
2/6	Enthalpy	1
2/11	Heat capacity	1
2/16	Entropy	4
2/18	Temperature dependence of entropy	1
2/20	Third law of thermodynamics	2
2/23	Third law of thermodynamics	1

liquids, and gases. In a general discussion about entropy, the instructor asked the students which phase of matter would have the most entropy (solids, liquid, or gas). This discussion is captured in the following three argumentation schemes:

Scheme 6	Context of Argument: Entropy	Date:2/16
Claim	Gas molecules have the most entropy of solid, liquid, and gas phases of matter. (Multiple students)	
Data	"*It [the gas] has the least interactions*." (Luke)	
Warrant	"There aren't any restrictions on where the gas molecules can be placed." (Instructor)	
Backing	*Few interactions means there are a lot of ways to distribute the gas particles*. (Beth)	

Scheme 7	
Claim	Solids have the least entropy of solid, liquid, and gas phases of matter. (Multiple students)
Data	"*You can't change the way they are arranged, solid*." (Jane)
Warrant	*Particles in solids have fixed positions*. (Instructor)

Scheme 8	
Claim	The entropies of liquids are in between those of gases and solids. (Instructor)
Data	"*They're [the liquid particles] moving around a little bit, but not as far as in gases*." (Marie)

Warrant	"*Do they have to stay basically touching each other? Yeah. So they can't just go moving off, they have to stay relative to each other, we still have forces and interactions*." (Instructor)

In scheme 6, Luke provided the evidence that gas particles have few interactions with one another. The instructor linked these data to the claim that gases would have the least entropy by stating that fewer interactions would mean fewer restrictions on the movement and spacing of the particles. The validity of this warrant came from Beth's backing that no restrictions on where the gas molecules can be placed means that there are more ways to distribute the particles. This statement again alluded to a definition of entropy as a measure of the number of ways particles can be arranged in a system.

In scheme 7, Jane and the instructor reasoned that particles in a solid have fixed positions, which means that the position of the solid particles cannot be changed. In scheme 8, Marie and the instructor reasoned that the particles in a liquid move more than in solids, but the position of the particles cannot be changed as much as gas phase particles because of the intermolecular attractions holding the liquid particles together. In this series of arguments, the data and warrants in all referenced the motion and position of particles in solids, liquids, and gases.

Particulate-level descriptions of solids, liquids, and gases were central to the collective reasoning about thermodynamic concepts and processes. This example of a classroom chemistry practice explicates a chain of reasoning that is used in ten different arguments, across six class periods spanning 17 days in time, and for a variety of different kinds of tasks. That students used these lines of reasoning repeatedly as they discussed conceptually different material indicated that reasoning with the particulate-level description of the phases of matter had become a classroom chemistry practice.

In summary, we refer to this classroom chemistry practice as "Reasoning using particulate-level descriptions of the phases of matter." The practice consists of the following normative ways of reasoning: (a) Particles are spaced closest together in solids, intermediate in liquids, and farthest apart in gases. (b) Intermolecular interactions are strongest in solids, weaker in liquids, and are negligible in gases. (c) The motion of gas phase particles in solids is unrestricted, the motion of liquid particles is more constrained, while the motion of particles in the solid phase are limited to vibrations in fixed positions. (d) Particles in gases have more energy than particles in liquids, which have more energy than particles in solids. Evidence was provided in the previous section that substantiated item (c) as an idea that functions as if shared in this chemistry classroom. The substantiation of ideas (a), (b), and (d) have also been completed using criteria 1, 2 and 3, but are not presented in this paper.

CONCLUSION

In this paper, we identified a new criterion that can be used to determine the specific ways of reasoning that constitute a classroom chemistry practice. This new criterion is not limited to chemistry classes but can used, in conjunction with the two previously identified criteria, to determine the classroom practices in any classroom that actively engages students in the learning process. The specific criterion we discovered involved the repeated use of data or warrants to justify assertions.

As the reader might have noticed in the examples tendered, the teacher provided a majority of the warrants. Practically speaking, the teacher *is* a member of the classroom community, and hence, any analysis of whole class argumentation will necessarily include the teacher's contributions. There are two additional comments regarding the fact that in whole class discussions the teacher provided more warrants than the students. First, the vast majority of the warrants provided by the teacher were elaborations of statements made by a student. As detailed by Forman, Larreamendy-Joerns, Stein & Brown (1998), such elaborations are a form of revoicing. Revoicing is a way in which a teacher shows shared ownership of ideas. Hence, from the students' perspective, the teacher's warrants were likely connected to and related to their ideas. Second, we conjecture that it is likely that the high number of teacher-provided warrants was related to the nature of the instructional environment. Specifically, the structure of this classroom often utilized the whole class discussion as a time to "report back" the ideas deliberated during small group work. With this conjecture in mind, we examined the argumentation patterns in the small group work and found that there were many instances in which students provided warrants, but as they continued to deliberate the ideas, warrants began to drop off. As such, once the class reconvened for whole class discussion, the students may not have felt it necessary to once again provide the warrants. Indeed, small group discussions were characterized by extended argumentation sequences where students presented reasoning, rebutted arguments, and made competing claims. During the 5-week unit on thermodynamics, the focus group routinely offered rebuttals and counterarguments. Thus, despite the fact that there were few student-contributed warrants, rebuttals and counterarguments in whole class discussion, the POGIL physical chemistry students engaged in substantive argumentation during the class.

A main contribution of this paper is the further development of the use of Toulmin analysis to empirically document the ways of reasoning that students use as they solve problems, explain their thinking, and represent their ideas. Previous work demonstrated the rigor and usefulness of the methodology in mathematics classrooms (Cobb et al., 2001; Stephan & Rasmussen, 2002). The work reported here represents proof of how the methodology can be successfully adapted for use in an interactive physical chemistry classroom. In particular, we have developed a new criterion to identify as if shared ideas which can be used to demonstrate when particular ways of reasoning become part of normative chemistry classroom practices.

The analysis of the transcripts showed distinct differences in the nature and quality of student discourse and understanding of the concepts on different days of instruction. These differences raise the question of what promotes student discourse that is effective for learning. In particular, what is the structure of materials that promotes productive discourse? Is there a pattern to the types of POGIL activities that result in rich argumentation schemes and evidence of student learning? What instructional strategies promote productive discourse? What discourse interaction patterns promote or constrain argumentation patterns in the whole class discussion? Previous research related to these questions has analyzed how differences in classroom discourse impact student understanding (e.g., Hogan, Nastasi & Pressley, 1999; Pierson-Bishop & Whitacre, 2010). Other studies have focused on how teachers can change their instructional practices to facilitate more student-led discussion by either decreasing their role in the generation of ideas and increasing their role in shaping and guiding those ideas (Nathan & Knuth, 2003; Rittenhouse, 1999) or by modeling ways for students to engage in productive mathematical argumentation (Lampert, 1990).

The methodology to analyze classroom discourse developed in this report contributes to this body of work by offering an empirical way to document the nature and quality of classroom discussion as it relates to the development of scientific or mathematical concepts. Many have pointed to the role of argumentation in learning (e.g., Osborne, 2010; Sfard, 2007), but few rigorous methodologies exist to coordinate classroom debate with the development of concepts and accepted scientific ways of reasoning. This paper makes a contribution in this direction.

In ongoing work, we are furthering the methodology by exploring ways to coordinate the Toulmin analysis with an analysis of the nature of curricular materials and instructional use of these materials. The results of this ongoing work may provide additional insights into how instructional strategies and the design of curricular materials improve student understanding of chemistry and the use of mathematical inscriptions in chemistry. These insights can then be applied to develop improved models for curriculum development and instructor pedagogical strategies.

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