Adapting a Methodology for Documenting Collective Growth to an Undergraduate Physical Chemistry Class

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In physical chemistry classrooms mathematical equations and symbols are commonly used to describe theoretical constructs and experimental observations, but few studies have investigated students' understanding of such equations and their connections to physical processes or measurements. The abstractness and conceptual content of these equations is frequently very high and understanding the connection between mathematical inscriptions and the physical macroscopic or microscopic knowledge they convey about a system is at the heart of physical chemistry. The meaning imparted by the mathematical equations allows physical chemists to have a common language for communication and inquiry. Familiarity and fluency with this symbolic language is essential for the acquisition of expertise (Kozma & Russell, 1997). For some students it is feared that the symbols are devoid of any physical meaning, and that an equation such as a partial derivative is an alphabet soup of Greek and English letters rather than conveying how a state variable of a system changes with respect to one variable while others are held constant.

In this report we investigate the meanings that developed for one physical chemistry class in a unit that made extensive use of mathematical equations and symbols to describe physical processes and measurements. Our analysis of the ways of reasoning through classroom interaction is compatible with the relatively recent emphasis of mathematics and science education research that focuses on how communities of learners establish ideas (Rasmussen, Zandieh, & Wawro, 2009; Saxe, et al., 2009). A theoretical and pragmatic concern that has emerged from this area of research is the documentation of the normative or collective ways of reasoning that develop as learners engage in mathematical or scientific problem solving and discussion. One promising method for analyzing the collective production of meaning uses a three-phase approach grounded in Toulmin's (1958) argumentation scheme (Rasmussen & Stephan, 2008). The development of this new method of analyzing student interactions and construction of knowledge along with the increased adoption of inquiry methods to teach physical chemistry provide a unique opportunity to investigate how students develop understanding of mathematical inscriptions in physical chemistry.

Frameworks for social construction of meaning in learners

In the early 20th century educational researchers like Piaget contended that learning was largely an individual accomplishment. However even researchers like Piaget acknowledged that social learning contexts and cultural tools could serve as catalysts for cognitive development and thus were important to the individual's development (Phillips, 2003b; Piaget, 1926). More recent learning theories like social constructivism acknowledge a far greater role of cultural tools and social context in the learning process. Social constructivism emphasizes the necessity of explaining learning in terms of social processes rather than as a solely individual endeavor and stresses that the social and individual learning processes are equally important and occur simultaneously (Cobb & Yackel, 1996; Phillips, 2003a, 2003b).

From a social constructivist perspective, the process of making sense of the language of physical chemistry and making sense of the chemical concepts that the language describes occurs simultaneously and the mathematical and linguistic tools and symbols that students use to communicate chemical understanding are an integral part of the development of students' conceptual understandings (Cobb, 1994; Cobb & Yackel, 1996). For instance, in order for a student to understand how the volume of an ideal gas changes with temperature, the student must learn to interpret mathematical symbols like $\left(\frac{\partial V}{\partial T}\right)_P$ and must also understand how partial derivatives of mathematical functions relate to physical changes in chemical systems.

Learning in a social setting results both from the process of internalization of cultural symbols and from participation in the community setting (Phillips, 2003b). Engaging in the social practices of the classroom community provides students with an opportunity to construct their own understanding of concepts (Phillips, 2003b). As students make sense of these concepts and cultural tools for themselves, their own interaction with others in the classroom may evolve, and so the collective classroom activities develop along with the individual students' understandings (Rasmussen & Stephan, 2008).

Active Learning in Physical Chemistry Classrooms

The application of Toulmin analysis and other discourse analysis techniques requires the use of a classroom that involves active student participation and discussion. POGIL, Process Oriented Guided Inquiry Learning (Farrell, Moog, & Spencer, 1999; Spencer & Moog, 2008) is the particular type of inquiry undergraduate chemistry course environment in which this study was conducted. Since its inception in 2003, the POGIL project has developed and disseminated curricular materials that promote active learning based on a constructivist approach (Moog, 2006; Spencer, et al., 2003). In recent years, numerous articles have been published in the literature describing the POGIL approach (Farrell, et al., 1999; Hanson & Wolfskill, 1998; Hanson & Wolfskill, 2000; Spencer, 1999) and its positive impact on student performance in a variety of institutional contexts (Hanson & Apple, 2004; Lewis & Lewis, 2005). POGIL materials for teaching thermodynamics, and quantum mechanics and spectroscopy, are commercially available, and have been classroom tested for many years (Spencer, Moog, & Farrell, 2004a, 2004b). The POGIL materials are 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 equation 1 [$G \equiv U + PV - TS$] using grammatically correct English sentences.” and "Use a grammatically correct English sentence to explain the meaning of the derivative ...” (Spencer, et al., 2004b). Thus the students are prompted to discuss and negotiate the meaning of the mathematical equations and concepts under study.

POGIL implementations are by their very nature oriented toward small group discussion. In a POGIL environment, students work in teams of three to five students on materials that provide data and prompts for students to analyze data and explain concepts. 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. The whole class discussion typically focuses more on ensuring all groups have a “correct” answer rather than fostering whole class discussion of ideas. Having students work in groups and engage in interactive whole class discussion is a pedagogical strategy that has its roots in a variety of learning theories including socio-cultural learning theory (Vygotsky, 1978), situated cognition (Brown, Collins, & Duguid, 1989; Lave, 1988; Orgill, 2007), and socio-constructivism (Ferguson, 2007; Piaget, 1932). These social theories of learning offer a lens through which to view and explain how learning takes place in a classroom, and detailed methods for documenting student learning as they engage in such collective activities are beginning to emerge.

Toulmin Analysis and the Adaptation to a Physical Chemistry Classroom

The methodological approach we take builds on and extends the approach detailed by Rasmussen and 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. This particular methodology grew out a specific type of inquiry oriented mathematics classes. Specifically, these inquiry-oriented classrooms characteristically have whole class discussions in which teachers routinely inquire into how their students are thinking on the one hand, and where students routinely inquire into challenging problems on the other hand (Rasmussen, Marrongelle, & Kwon, 2007). Student inquiry into challenging problems involves explaining and presenting one's own reasoning, as well as attending to, questioning, and commenting on the reasoning of others. Such classrooms allow researchers to trace the growth of ideas as they are initiated and constituted via classroom discussion.

In his seminal work, Toulmin (1958) created a model to describe the structure and function of certain parts of an individual's argument. Figure 1 illustrates that, for Toulmin, the core of an argument consists of three parts: the data, the claim, and the warrant. In any argumentation, 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 is made. When this type of challenge is made and a presenter provides more clarification that connects the data to the conclusion, the presenter is providing a *warrant,* or a connector between the two. 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.

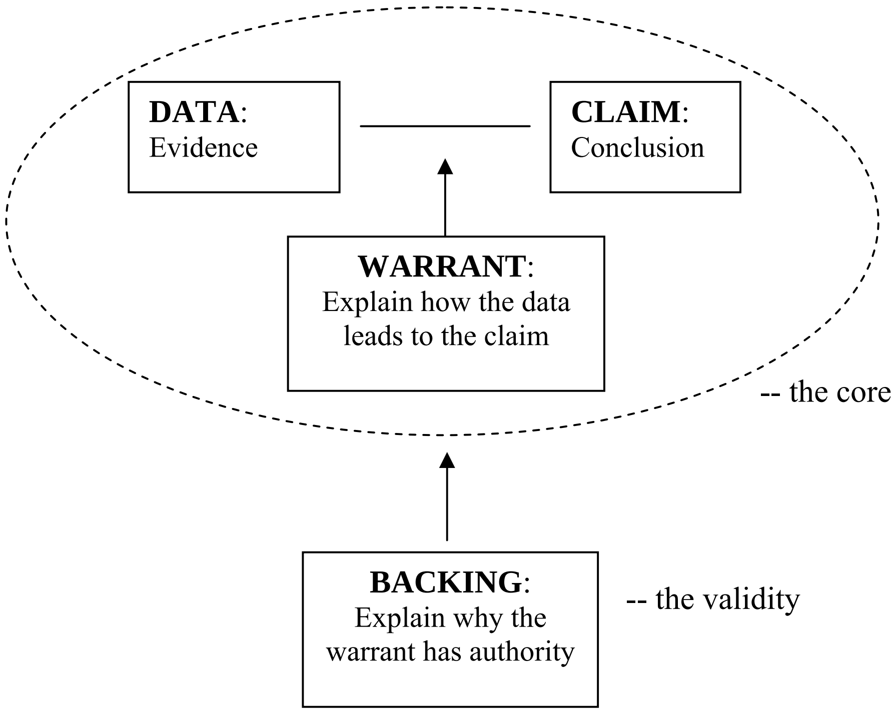

Figure 1. Toulmin's model of argumentation.

The methodology developed by Rasmussen and Stephan (2008) to document and analyze student learning in interactive classrooms is a rigorous three-phase approach that uses Toulmin's model of argumentation. The first phase begins by creating transcripts of every whole class discussion. Next, Toulmin's model is used to create a sequence of argumentation schemes interpreting the discourse on each day, resulting in an argumentation log across all whole class discussions. The second phase of the analysis involves taking the argumentation log as data itself and looking across all class sessions to see what mathematical (or scientific) ideas expressed in the arguments become part of the group's normative ways of reasoning, i.e.

function as-if-shared. The following two criteria are used to determine when an idea functions as-if-shared: 1) When the backings and/or warrants for particular claim initially are present but then drop off, or 2) When any of the four parts of an argument (the data, warrant, claim, or backing) shifts position within subsequent arguments. Next, a mathematical or scientific ideas chart is created for each day that includes three columns: a column for the ideas that now function "as-if-shared"; a column of the ideas that were discussed that will be monitored to see if they subsequently function as if they were shared; and a third column of additional comments, both practical and theoretical. In the third phase of the analysis, the ideas from the as-if-shared column of the second phase are organized around specific mathematical or scientific activities. Each cluster is then given a theme that indicates the common thread among the related ideas. Each of these themed clusters is referred to as a classroom mathematical practice. These specific themes constitute the collective mathematical or scientific practice of the classroom community.

Methodology

Our classroom observations focused on whole class discussions of the entire class and the small group discussions of a group of four students during the thermodynamics semester of an undergraduate POGIL physical chemistry class. We believe that shifts in classroom discourse patterns can indicate changes in small group and collective classroom understanding of chemistry concepts. To explore these discourse patterns, our analysis uses Toulmin's (1958) argumentation scheme as an analytical framework to document and analyze the classroom activities.

Five weeks of videotape transcripts of whole class discussion in a POGIL physical chemistry class were analyzed as part of an NSF-funded project to adapt Toulmin Analysis for use in chemistry classrooms. The first phase of the analysis was to create argumentation logs for each class session.

One of the challenges in adapting Toulmin analysis from mathematics education research to chemistry education research is the specific use of data in chemistry. Generally, when a chemist refers to data, they are referring to observations and/or measurements that were obtained from an experiment. In analyzing the classroom discourse, a practice of looking for key phrases to identify data in the sense of argumentation schemes had to be used to eliminate confusion on what was serving as data for the argument. Typical argumentation structures will follow the pattern of *data so claim* or *claim because data*. For example, when the Third Law of Thermodynamics was introduced, students were asked to write an expression for calculating the entropy of water at 273.K and 1 bar pressure. One student, Adam, made the *claim* that $\Delta S = \Delta H/T$. Another classmate, Melissa, asked “Why?” Adam responded, “Cause in, the phase change. It's at equilibrium, so you use this equation.” In terms of Toulmin’s scheme, Adam made a *claim* that $\Delta S = \Delta H/T$ and gave evidence (*data*) that the system being analyzed was undergoing a phase change. In this case Adam also clarified how his evidence related to his conclusion (*warrant*) by connecting the phase change to an equilibrium state and the appropriate equation to use under those circumstances. Sometimes a student or the instructor may challenge a student to clarify how his evidence relates to his conclusion, but in this case Adam provided both the data and the warrant when his claim was challenged.

The second phase of the analysis focused on the argumentation logs for the whole class discussions. In the original methodology, the process was to look across multiple class sessions to see what ideas expressed in the arguments became part of the group’s normative ways of reasoning. As stated previously, accomplishing this task is based on two criteria: 1) When the backings and/or warrants for particular claim initially are present but then drop off, or 2) When any of the four parts of an argument (the data, warrant, claim, or backing) shifts position within subsequent arguments.

In this study, the structure of what is referred to as "critical thinking questions" in the POGIL materials created an artificial framework for student reasoning. The questions would sometimes provide data and ask for a claim, or provide a claim and ask for the data to support it. These questions also frequently asked for warrants, although there were very few instances of backings in the analyzed arguments. As such, we were only moderately successful in employing the two criteria for determining the normative ways of reasoning.

This challenge in utilizing the two criteria led to a central and unexpected methodological finding. In particular, we developed a new criterion for determining the cluster or common thread among the related ideas that function as-if shared. It is this broader theme that constitutes the classroom chemistry practice. This new criterion emerged from analysis of argumentation logs across multiple class sessions, which showed that there were certain ideas that students repeatedly used in their explanations and justifications. More specifically, careful review of the argumentation logs revealed that certain ideas were repeatedly used as either data and/or warrants. Thus, the new criterion we discovered was the repeated use of certain ideas as either data or warrants. Reasoning with these particular ideas constitutes a classroom chemistry practice.

Example data and analysis for one theme

For example, one classroom chemistry practice that we identified was "Reasoning with the phase of a substance." In this practice, students used phase states in their arguments when discussing topics such as heat capacity, entropy, entropy changes, and enthalpy changes. A series of argumentation logs are shown below. In general, the discourse has been summarized. Direct quotes are indicated by the use of italics. The specific instances where students use characteristics of phases in their argument have been underlined.

(38:51–39:17) WCD; CTQ 5; 2/11

Claim: Gas should have the lower heat capacity and water would have the higher heat capacity (Marie)

Data: <u>*Gas has less interactions*</u> (Helen)

Warrant: *Water's got all of that hydrogen bonding going on, so I can use part of that energy to overcome the hydrogen bonding and break down those forces. In gas we're saying the forces are pretty minimal, so I don't have nearly the number of forces* (Teacher)

(18:46-19:26) WCD; 2/16

Claim: Gas has the most entropy (Multiple students)

Data: <u>It has the least interactions</u> (Luke/Helen)

Warrant: I don't really have any restrictions on where I put the gas molecules (Teacher)

Backing: There are a lot of ways to distribute the particles (Teacher/Beth)

(19:26-19:49) WCD; 2/16

Claim: Solids have the least amount of entropy (Multiple students)

Data: <u>Can't change it; atoms in a fixed position</u> (Jane)

(39:53-40:46) WCD; CTQ 12; 2/18

Claim: Enthalpy of reaction is positive for the melting of ice (Textbook/Teacher)

Data: Because it's going from a solid to a liquid (Zane)

Warrant1: going from a solid to a liquid requires heat because *it* [the solid] *breaks down* (Zane)

Warrant2: We put energy in to go from solid to the liquid so we give the molecules enough energy to move around (Teacher)

Backing: *Liquids are a more high entropy state than solids are* (Teacher) [Backing comes in as a response to some misconceptions involving "breaking bonds" related to warrant 2]

(39:36-39:40) WCD; CTQ 9b; 2/20

Claim: The entropy of H_2O liquid is greater than the entropy of H_2O solid under the same conditions (Melissa)

Data: It's going from a phase change from a solid to a liquid (Melissa)

Warrant: we know that liquids have more entropy than solids even though they're at the same temperature (Teacher)

In each of these arguments students have used their knowledge of the characteristics of solids, liquids, and gases to reason about the thermodynamic concepts and/or processes being analyzed. Students continue to use information about the phase (solid, liquid, or gas) of a substance repeatedly as data or warrants to make claims about new physical chemistry concepts throughout the data we analyzed. We consider this theme, in which students use information about the phase of a substance, to comprise a classroom chemistry practice.

Emergent findings

The nature of the POGIL guided inquiry materials required some modification to the methodology described by Rasmussen and Stephan. In general, however, this method of analysis is proving to be a powerful analytic tool to analyze classroom discourse and the evolution of student ideas. Our primary findings revealed the following five classroom chemistry practices: (1) Using phase states to make claims about motion, interactions, or energy; (2) Inferring energy states from the number of bonds; (3) Interpreting and using state functions; (4) Reasoning about equilibrium; (5) Reasoning about spontaneous processes. Each of these practices was determined using the new criterion of repeated use of certain ideas as either data or warrants. We believe that these themes reveal the structure of knowledge in the discipline and that they have pedagogical importance. The analysis also shows that students frequently do not understand how to interpret the meaning conveyed by mathematical symbols. There is also evidence in the transcript analysis that students are not successfully making connections between mathematical inscriptions and the physical macroscopic or microscopic knowledge they convey about a system. These findings point to the need for additional analysis into how students (individually and as a community) translate mathematical equations and symbols into descriptions of the macroscopic system under investigation.

This study also offers evidence that the use of Toulmin analysis to document and analyze student learning provides a theoretically based mechanism to view and explain 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. The work reported here represents an existence proof of how the methodology can be successfully adapted for use in a POGIL physical chemistry classroom.

Future Work

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? The documentation and analysis of student discourse using Toulmin analysis provides the opportunity to correlate the nature of curricular materials and instructional strategies to student learning. The results of the research will 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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