Engaging the Invisible in Visible Ways: Designing Activity for Chemical Reasoning

Heena Lakhani

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Reading Committee:

Philip Bell, Chair

Kara Jackson

Mark Windschitl

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Abstract

Engaging the Invisible in Visible Ways: Designing Activity for Chemical Reasoning

Heena Lakhani

Chair of the Supervisory Committee:
Dr. Philip Bell
Learning Sciences and Human Development

In the learning of chemistry, and science, it is critical for learners to be able to engage with the "invisible" science concepts in ways that are meaningful and productive. The present set of studies will be exploring the role of activity systems in this process, specifically the role that mediating objects play in supporting learners to engage in meaning making with scientific concepts. This dissertation will leverage conceptual frameworks in chemistry education research and activity theory, to show how mediating objects embedded within activity systems can make visible the various aspects of chemistry and science learning. The studies will show how students and teachers use various mediating objects (e.g., tools, conceptual sketches, and practical measures) to make sense of the different levels of representation in chemical thinking, as defined by chemistry and science education frameworks (e.g., symbolic, macroscopic and sub-microscopic connections, and students' conceptual understandings and experiences in the science

classroom). Collectively, these studies will show how learners engage in activity with mediating objects, attending to how these objects operate to make the relevant dimensions of learning salient during meaning making. These studies will then be used to put forth design principles about how to design and use mediating artifacts to engage the invisible aspects of science teaching and learning in visible ways.

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DEDICATION

To my mother, Nazleen.

Chapter 1. INTRODUCTION

In the domain of science, learners are constantly making sense of concepts that are invisible to the naked eye. For learning to be effective, these concepts must have a way to become visible to them so that they can reason and interact with them in meaningful and productive ways. This dissertation will be exploring the role that activity plays in this process; specifically, it will explore how activity systems support learning through mediating objects that make invisible concepts in science visible.

The overall goal of the studies presented here will be to present a learning sciences approach to the design of activities in science, specifically chemistry. The Cambridge Handbook of the Learning Sciences notes that the field of learning sciences is both interdisciplinary and multidisciplinary, and addresses multiple questions, including how people learn and how learning environments can support students in this process (Sawyer, 2005). Learning and the design of learning environments are intricately linked, where concepts are culturally mediated (Cole and Wertsch, 1996) and developed through activity (Brown, Collins and Duguid, 1989). This situated perspective of learning foregrounds and studies the "practices that communities have historically developed and dynamically shaped in order to accomplish that they value," (p. 686, Nasir, et al., 2014). In the field of chemistry, there are multiple representational levels which will be described using the chemistry education more formally later in the chapter. These levels have been identified and characterized as a foundational framework for discipline-based education research, specifically in chemistry (NRC, 2012). The ideas and concepts engaged in the chemistry education framework are often invisible and can be inaccessible. Thus, the learning environment in a chemistry context, should involve activity systems that attend to the arrangement of cognitive, social, and material mechanisms that support disciplinary ways of knowing and produce an epistemic culture (Knorr Cetina, 1999; Lehrer, 2009).

The studies presented in this dissertation are drawn mostly from chemistry learning contexts and include high school students, undergraduate students, and in-service chemistry and middle school science teachers. Each study focuses on two important and shared aspects. First, how a mediating object enables learners to engage in sense-making around chemistry content, specifically by making visible the invisible aspects of chemical reasoning. And second, through this activity, how learners can develop representational competence. In order to make sense of the studies, this dissertation will be leveraging conceptual frameworks in chemistry education and activity theory. While these frameworks will be unpacked further in the subsequent chapters, this chapter will provide an introduction to each of these frameworks and how they will be leveraged in the subsequent chapters.

Johnstone (1993) proposed an organizational framework for chemistry education that categorizes the three basic components or levels of representation in chemistry: macrochemistry, microchemistry, and representational chemistry. The microchemistry (i.e., macro level) component involves what is tangible, edible, and visible; in other words, what is observed and/or experienced. Talanquer (2011) has expanded on this to include not only what is experienced directly through the senses but also indirectly through instrumentation. The microchemistry component (i.e., micro level) involves the molecular, atomic, and kinetic levels of understanding (Johnstone, 1993). This has been expanded to include the explanatory and predictive aspects of theoretical models that chemists have developed to make sense of what is experienced (Talanquer, 2011). The representational chemistry component (i.e., symbolic level) includes the symbols, equations, stoichiometry, and mathematics that are used to represent and make sense of the core models of chemistry (Talanquer, 2011). Together, these three components comprise the chemistry education framework or what is called the chemistry triplet (Talanquer, 2011).

For example, when making sense of a chemical phenomenon, such as what happens when vinegar and baking soda are mixed. An example of a causal explanation that connects the three levels of chemical representation would be as follows: When vinegar (an acid) is added to baking soda (a base) and water in a glass, the mixture foams up and is released quickly (macroscopic or observational account). This is because the atoms in the vinegar and baking soda react with each other via an acid-base reaction, where the vinegar gives its proton (H^+) to the baking soda to then form a new compound (carbonic acid), which then decomposes into water and carbon dioxide (sub-microscopic account). This reaction occurs quickly, so when the carbon dioxide is released, it bubbles forth as a gas through the mixture (sub-microscopic level being connected to the macroscopic account). The chemical reaction can be represented using the following chemical equation (symbolic or representational account):

$$NaHCO_3 + HC_2H_3O_2 \rightarrow NaC_2H_3O_2 + H_2O + CO_2$$

The causal explanation provided not only includes all three representational elements, but it connects each level of representation.

The chemistry triplet, as currently described, does not take into account students' interests and experiences. More recent literature has discussed expanding the chemistry triplet to include the "human element" as a dimension in the chemistry education framework (Mahaffy, 2004). The human element broadly captures contexts that are relevant for students and society in chemistry teaching and learning. This call for including the human element in the design of science learning is not unique to chemistry. Researchers have emphasized the importance of attending to students' interests in the science classroom as it improves their conceptual learning

(Rivet and Krajcik, 2008) and helps to achieve meaningful learning across multiple settings and periods of time (Bell, et al., 2012).

Through activity, learners come together to make sense of ideas through social interactions and/or material artifacts (Cole, 1998). The current studies will be investigating how the various aspects of chemical reasoning, involving the chemical triplet as well as the dimension of the "human element", can be mediated through tools and/or social processes. The studies will be attending to how individuals are using the mediating objects to make sense of chemical ideas/scenarios as well as how these mediating objects can support social and individual cognition (Cole & Wertsch, 1996) around foundational ideas in chemistry. Thus, through these questions, one can understand how the processes of sense-making are being supported through the mediating object (which will be defined as a process outcome) but also how these processes are supporting the development of representational competence (which will be defined as a representational competence outcome).

Representations and their development are central to the production of knowledge in the sciences (Latour, 1999) and have been theorized from both learning sciences and science education perspectives. These representations can take on many forms such as equations, diagrams, sketches, etc. They serve multiple functions including: making invisible entities explicit, enabling these entities to be manipulated through rules and interactions, and serving as a predictions about phenomenon (Windschitl, Thompson, and Braaten, 2008; Cooper, Stieff, and DeSutter, 2017; Kozma, et al, 2000). Representational competence is critical for students to develop conceptual understanding in science (Lehrer & Schauble, 2006), and in chemistry, enables students to move flexibly across the three levels of chemical representation (i.e., the chemistry triplet) for any given chemical phenomenon (Kozma, et al., 2000). The causal explanation of what happens when acid and vinegar are mixed does exactly this. It moves from the observable/macroscopic level to the sub-microscopic/particulate level and then to the representational/symbolic level. It is important to note that there is representational competence for each level, in of itself, and activity systems can be focused on the development of representational competence for that level. The activity systems in these studies will be investigating the sense-making around a mediating object (process outcome). Furthermore, these studies will also be analyzing the development of representational competence, as a consequence of engaging in these activity systems (representational competence outcome).

The set of studies proposed in this dissertation investigate the role that mediating objects can play in in making visible the invisible aspects of chemical reasoning. Table 1 provides a brief description of these studies, showing who the learners are, what is being made visible through activity, and the research questions associated with the study. The quantities that students reason about when problem-solving in chemistry is both foundational and is often not made visible during instruction. Thus, the first study (chapter 2) will seek to understand how a tool can support students in their understanding of mathematical relationships in chemical dimensional analysis, which is a method that chemists use to reason between macroscopic (e.g., mass) and microscopic quantities (e.g., number of particles). This study observed a group of students in a high school chemistry class as they used a tool in a laboratory exercise to make sense of chemical scenarios, in which they are reasoning about how to go between different quantities (e.g., mass to number of particles). It will show how the students are using the tool in both conceptual and algorithmic ways (process outcome). This study will also look at exit ticket data after the laboratory exercise to understand how the tool mediated their understanding of quantities and quantity relationships in chemical dimensional analysis (representational competence outcome). Thus, this study informs how a tool can support students' meaning making around foundational quantities in chemistry.

The sub-microscopic account can help students make sense of the observed phenomenon. Thus, the second study (chapter 3) seeks to understand how a conceptual sketch can support students in their understanding of the sub-microscopic interactions that are occurring in a chemical event, and how this understanding can be leveraged to explain what they observe at the macroscopic level. For a series of chemical events, students were asked to write down what they observed (macroscopic level) and how the sub-microscopic interactions could be used to explain what they observed. This study observed two groups of students in an introductory undergraduate chemistry course. In one group, the students were asked to engage in conceptual sketching, in which they were asked to represent the particles and the interactions amongst them; in the other group, the students did not engage in any conceptual sketching. The study will be looking at the ways the students made sense of the entities and their interactions using a conceptual sketch (process outcome). This study will also look at students' explanations of how the sub-microscopic level account can be used to support the macroscopic/observational account (representational competence outcome). Thus, this study informs how a conceptual sketch can support students meaning making between the macroscopic and sub-microscopic levels to make sense of a chemical phenomenon.

The diversity of students' conceptual understandings and experiences are also not easily made visible in instruction. The third study (chapter 4) seeks to understand how in-service high school chemistry and middle school science teachers can be supported through professional learning experiences to make sense of: 1) facets of students thinking in chemistry and 2) students' experiences in in the science classroom, respectively. These two aspects are "invisible" in that there are more calls to attend to students' facets of thinking in instruction as they can support building and refining new knowledge (Bell and Minstrell, 2016; Minstrell, 1989) and the importance of connecting science instruction to students' every day and cultural lives (Bell, et al., 2012). This study will show how professional development (PD) sessions were designed for science teachers in each of these two aspects, using a set of practical measures. Practical measures are a mechanism to sense on-the-ground implementation through iterative inquiry for educational improvement efforts (Yeager, et al., 2013) and the data is "collected, analyzed, and used within the daily work lives of practitioners" (Russell and Grunow, 2015). The data from the practical measures comes from teachers and students responding to weekly surveys about their experiences in the science classroom. Thus, the practical measures serve as a source of understanding and designing around problems of practice; making visible how science teachers' perspectives on student understanding and how students are experiencing science instruction. In this frame, the practical measures serve as a boundary object, in that they serve as a bridging function between the PD space and teachers' experiences in the science classroom (Star, 1989; Akkerman and Bakker, 2011). The data in this chapter will talk about how the practical measures informed the design of the PD sessions with science teachers and how the teachers engaged in sense-making in these sessions. Thus, there are two processes that will be described in this chapter. The first process describes how practical measures data made visible teachers' and students' experiences in science class, and how this data was used to inform the design of PD sessions. The second process describes how the teachers' sense-making around this data, particularly how the activities made visible the different dimensions of science teaching.

Through the set of studies proposed above, this dissertation will show how activity systems with mediating objects can make visible the various aspects of chemistry and science learning. Chapters 2 and 3 show how mediated objects such as tools and conceptual sketches, respectively, can support students to make sense of the different levels of representation in chemical thinking. Chapter 2 demonstrates the importance of attending to high school chemistry students' conceptual and algorithmic understandings of dimensional analysis and how a tool can support sense-making around dimensional analysis that integrates the conceptual and algorithmic aspects of it. Chapter 3 shows how conceptual sketching can support undergraduate chemistry students to make sense of chemical phenomena by enabling them to visualize the invisible entities involved, and to then use this understanding to explain an observable event.

Chapter 4 discusses how to design activity to support teachers in the sense-making of students' facets of thinking in science as well as their experiences in the science classroom in both chemistry and broader science contexts. The design of the activity takes into account teachers' self-reports about their practice and leverages their students' work and voices through the use of practical measures. Through activity, teachers learn how to make visible and engage students' facets of thinking and their experiences in science classroom.

Collectively, these studies will show how specific mediating objects operate to make relevant dimensions of learning salient in instruction and what one can learn about the qualities of mediating artifacts in meaning-making and learning. The studies will show how the learners are engaging in activity with these mediating objects, and the sense-making acts that they use to make sense of chemical and scientific concepts. These studies will then be used to put forth design principles about how to design and use mediating artifacts to engage the invisible aspects of science teaching and learning in visible ways.

Table 1 Brief descriptions of the three studies in this dissertation, including the learners, mediating objects in the activity systems, and associated research questions.

Learners	Chapter	Mediating Object	Research Questions
High school students in a general chemistry class	2: Sense-making around the quantities & quantity relationships in chemical dimensional analysis	Tool that makes explicit quantities & quantity relationships	1. How can a cognitive tool support students' sense-making around quantities and quantity relationships during chemical dimensional analysis?
Undergraduate students in a general chemistry course	3: Using conceptual sketches to make sense of phenomena at the microscopic levels	Conceptual sketch that makes explicit microscopic components and its interactions	1. In what ways do sketches affect students' explanations of chemical events at the sub-microscopic levels? 2. How do students represent the interactions in a chemical phenomenon in their sketches as compared to their causal explanations?
High school chemistry teachers & Middle school science teachers	4: Using practical measures to guide improvement, specifically supporting in-service science teachers around students' facets of thinking and the student experience in science class	Using practical measures data to understand teachers' and students' experiences in the science class, and to design professional learning experiences that support teachers to: 1) identify and integrate facets of student thinking instruction and 2) engagement and understanding around collecting data around the student experience in science	1. How can practical measures be used to guide the design of professional learning experiences with high school chemistry teachers? 2. In what ways can professional development support engagement and understanding around collecting data around students' interests and experience in the science classroom?

Chapter 2. SENSE-MAKING AROUND THE QUANTITIES AND QUANTITY RELATIONSHIPS IN CHEMICAL DIMENSIONAL ANALYSIS

Mathematics serves many functions in a scientific context including being one of the "languages of science" (NRC, 2012, p. 64). The Framework for K-12 Science Education describes mathematics as a "fundamental tool for representing physical variables and their relationships" in science (NRC, 2012, p. 51). The language of mathematics in a scientific context should enable students to express and reason about the relationships between physical variables in quantitative or algorithmic ways. In chemistry, one of the foundational skills is to be able to reason flexibly between macroscopic and sub-microscopic quantities through mathematical thinking. This requires students to be able to reason about how mass relates to the number of particles, where particles can be atoms, molecules, or formula units. The NGSS (NGSS Lead States, 2013) identifies a physical science educational standard where students should be able to use "mathematical ideas to communicate the translation of these relationships to the macroscopic scale using the mole as the conversion from the atomic to the macroscopic scale. Emphasis is on assessing students' use of mathematical thinking and not on memorization and rote application of problem-solving techniques" (p. 82). There are several key ideas that can be extracted from The Framework for K-12 Science Education about mathematical thinking in scientific contexts such as how can science environments be designed can attend to both conceptual and algorithmic understandings, and how can they be integrated and weaved to together in problem-solving.

The present research focuses on students' understanding of the dimensions of dimensional analysis in chemistry: the process of going from mass to the number of particles occurs through the act of dimensional analysis (which will be described more formally later).

More importantly, the use of dimensional analysis is critical to engage in more complex chemical reasoning, such as making sense of chemical reactions and kinetics. To date, the extant research has focused on students' conceptual understandings about specific quantities in dimensional analysis such as the mole (Fang, Hart, and Clarke, 2016; Furio et al., 2000; Staver & Lumpe, 1995). However, little to no research has focused on students' conceptual understandings not just the algorithmic understandings of the process of chemical dimensional analysis, and how mediating tools can support students in their meaning-making around dimensional analysis.

This chapter will first talk about the components of dimensional analysis and how it can be approached in both conceptual and algorithmic ways. Second, it will describe the chemistry education framework, and the various levels of representation in chemical understanding. This will help frame where dimensional analysis fits in the scheme of chemical thinking. Third, it will describe the extant research around students' conceptual and algorithmic understandings in chemical contexts. Fourth, it will look at the role that mediated activity through the use of social and material means to support chemical thinking. It will look at how chemists use mediated activity to make sense of chemical ideas and it will then describe studies that demonstrate the role of mediated activity in facilitating students' understandings of the different levels of representation in chemistry. This will then situate and motivate the research questions for the current study.

2.1 DIMENSIONAL ANALYSIS IN CHEMISTRY

In an introductory, foundational chemistry textbook, Brown, LeMay & Bursten (1997) situate chemical dimensional analysis as allowing one to make "conversions of mass to moles and of moles to mass are frequently encountered in calculations using the mole concept" (p. 81). They define the following steps in dimensional analysis (p. 26):

1. What data are we given in the problem?
2. What quantity do we wish to obtain?
3. What conversion factors do we have available to take us from the given quantity to the desired one?

Thus, dimensional analysis involves students identifying which quantity they start with, what quantity they wish to obtain, and the appropriate quantity relationships between the two. The use of the terminology “quantity” and “quantity relationships” is intentional so that it draws explicit attention to the aspects of dimensional analysis using parallel language. According to Dierks, Weninger, and Herron (1985), “in science, normally quantities are related rather than numbers.” They define a quantity “as an attribute of a phenomenon or of a body, which is susceptible to qualitative identification and quantitative determination.” Thus, examples of quantities in chemistry include mass, moles, and number of particles. To convert from mass to the number of moles would require a conversion factor or a quantity relationship where one needs the relationship between mass and moles, which is the molar mass.

When thinking about the aspects of dimensional analysis, there are multiple ways to approach what is learned and how it is learned. For what is learned, there are both algorithmic and conceptual components to dimensional analysis, which become weaved together during the act. The algorithmic component involves setting up and executing the steps in dimensional analysis. This includes the three steps identified earlier from Brown, LeMay, and Bursten (1997). As for the conceptual component of dimensional analysis, there are multiple conceptual understandings that one can have around dimensional analysis. This can include but is not limited to: the reasoning around each step in dimensional analysis, the reasoning that takes place to decide in which situations one needs to engage in dimensional analysis, and being able to reason conceptually around relationships between quantities. This is not meant to be an exhaustive list of all conceptual understandings, rather, it is meant to open up the various ways in which conceptual understandings about dimensional analysis can manifest themselves.

For the question about how dimensional analysis is learned, one needs to understand the activities and tools that can help students understand the algorithmic and conceptual aspects (or dimensions) of dimensional analysis. The activity itself can guide students in multiple ways including: setting up and executing the steps in dimensional analysis (algorithmic) as well as develop reasoning about the steps, quantities, and situations involves in dimensional analysis (conceptual). Again, the goal is not to create an exhaustive list of all possibilities, but rather, to understand that activity can be generative and expansive (Cole and Engeström, 1993) and allow students to reason in flexible ways such that they are able to recruit their prior knowledge and explore disciplinary concepts that are relevant to and situated in the current context.

2.2 CHEMISTRY EDUCATION FRAMEWORK

Johnstone (1993) proposed a framework for chemistry education, which included the macroscopic (observational), sub-microscopic (particulate-based interactions), and the symbolic (symbols, equations, and mathematics) levels of representation. This is referred to as the "chemistry triplet." Each of these levels of reasoning is important in chemical thinking, and the current research is focused on students' understanding of the symbolic level. Specifically, the mathematics that are involved in reasoning about the quantities and quantity relationships involved in dimensional analysis.

When thinking about how dimensional analysis is situated within the chemistry triplet, one must ask the following question: in what ways is dimensional analysis being leveraged in chemical reasoning? In one way, dimensional analysis can be leveraged to support reasoning about chemical concepts such as molarity, pH, chemical reactions, etc. In this case, it is essential for the symbolic representation to be connected to the macro and micro levels of representation for deep conceptual understanding. In another way, dimensional analysis can be framed is as an end goal in of itself, with both conceptual and algorithmic aspects of understanding. As Talanquer (2011) points out, "I would claim that each of the components of the triplet can be approached qualitatively or quantitatively, conceptually or algorithmically, depending on the nature of the task and the particular characteristics of the teacher and the learner." (p. 186). Even Johnstone (1993) notes, "it is arrogant on our part to assume, or to insist, that every student studying chemistry for whatever purpose needs to operate within the triangle." This leads to two important aspects of understanding chemical dimensional analysis. First, it can both be viewed as a representational level of understanding within itself, as it is a foundational level of reasoning between quantities at the macroscopic and the sub-microscopic levels. And it can also be viewed as how it connects to the other representational levels in chemistry. The present research is concerned with the first view. Second, although chemical dimensional analysis tends to be viewed as an algorithmically-oriented act, however one can also view in conceptually. The conceptual aspects can become visible and supported if the design of classroom activity lends itself to it. The present research is interested in understanding the possibilities of conceptual expressions that can become possible through intentionally-designed activity.

2.3 Conceptual and Algorithmic Aspects of Chemistry

Historically, the research that has been at the intersection of conceptual chemistry and algorithmic thinking has predominantly shown that there is: 1) a dissociation of students' chemistry knowledge and the corresponding algorithmic knowledge, and 2) that students tend to be more successful at algorithmic questions as compared to the conceptual ones (Nurrenbern and

Pickering (1987); Sanger, 2005; Cracolice, Deming, and Ehlert (2008)). Nurrenbern and Pickering (1987) showed that first-year general chemistry students were more successful in solving algorithmic problems rather than conceptual questions in the areas of gas laws and stoichiometry. This research is further supported by the work of Cracolice, Deming, and Ehlert (2008) who showed that first-year general chemistry students were more successful at questions that were algorithmic rather than conceptual in nature. Furthermore, they observed a pattern where students who were categorized as “better” and “poorer” reasoners (as measured by a test of general scientific reasoning skills) performed better on the algorithmic questions as compared to the conceptual questions. Thus, the dissociation in students’ conceptual and algorithmic understandings seems to be robust across groups of students with varying scientific reasoning abilities. Other studies (Sanger, 2005) have looked more specifically at conceptual-specific difficulties that students have with chemistry topics that are algorithmic in nature. This has been shown in the domain of stoichiometry (Sanger, 2005), where students are able to balance equation but not be able to reason about what this means at the molecular level. Thus, the research literature has predominantly focused and shown that students can succeed in the procedural aspects of problem-solving, but do not succeed in the aspects related to conceptual reasoning. These studies have separated the algorithmic and conceptual aspects of problem-solving. This can be a productive way of assessing students algorithmic and conceptual understandings, but it is not the only way to assess these understandings. Students’ algorithmic and conceptual understandings can be assessed and displayed simultaneously in the course of activity, where the conceptual understandings are an emergent feature of students’ prior knowledge and their self-directed navigation of meaning-making.

2.4 MEDIATED ACTIVITY AND USE OF TOOLS IN CHEMICAL REASONING

Higher mental functions are always culturally mediated (Cole & Wertsch, 1996), and well-structured activity systems play an important role in situating and supporting the development of learning (Brown, Collins, and Duguid, 1989). There have been numerous studies that show how chemists use tools and how activities can connect students' macro, sub-micro, and the symbolic levels of understanding in chemistry. These studies have leveraged instructional technologies that have made explicit the connection between the levels of representation in chemistry. The studies foreground the development of jointly created processes between groups, where the role of activities is to guide the development of new and/or shared understandings.

In chemical reasoning, chemists have designed tools and representational systems that mediate what they can (macroscopic) and they cannot see (sub-microscopic) (Kozma, et al., 2000). In doing so, there are two important aspects of the mediated process: the material and the social. The material aspect attends to the surface features that can be perceived and manipulated; the social aspect attends to the semiotic, rhetorical processes that stand for unseen entities and processes (Kozma, et al., 2000). Both students (Kozma, 2000) and scientists (Kozma, et al., 2000) engage in material and social processes to make sense of chemical ideas that involves manipulating and moving flexibly between unseen and seen entities.

In the context of dimensional analysis in chemistry, instructional tools – as part of activity systems - can be designed that support the understanding of the components of dimensional analysis such that they emphasize the quantities or entities involved and the relationships amongst them. In dimensional analysis, students have to think about the starting quantity for the problem context, what is the desired quantity, and the appropriate quantity relationships that are necessary to go between the starting and desired quantities. A tool can be designed to help students navigate these relationships in a meaningful way, by making explicit the unseen entities in dimensional analysis: quantities and quantity relationships. Such that it enables them to think about the symbolic level of representation in chemistry in both a conceptual and algorithmic way (Talanquer, 2011).

2.5 Research questions

The present research is first looking at students' conceptual and algorithmic understandings of dimensional analysis. These two types of knowledge are fundamental to understanding dimensional analysis, and the present research will be probing each of these understandings separately. Given that dimensional analysis has been traditionally viewed as algorithmic in nature, an instructor may not think to (or know how to) attend to students' conceptual understanding of dimensional analysis and/or how to promote a more meaningful (not rote) understanding of the quantities and the quantity relationships or conversion factors in dimensional analysis. Thus, the first research question in this paper is interested in tackling is: ***In what ways do students exhibit conceptual understandings of chemical dimensional analysis during problem solving?***

A cognitive tool can guide students' understanding of the quantities and quantity relationships in dimensional analysis, and this process can be understood through the lens of activity theory (Engeström, 1987). Through activity, individual and/or groups of students can use a tool that can mediate the interaction between themselves and the object of the activity (Cole, 1998; Engeström, 1987; Jonassen and Rohrer-Murphy, 1999). The tool mediates the relationship between the subject(s) (i.e., student(s)) and the object of activity (i.e., understanding of quantities and quantity relationships in dimensional analysis). In the present study, the students used a tool in a laboratory activity to guide their understanding of how three key physical quantities in chemistry (i.e., mass, number of moles, and number of particles) relate to each other, and the quantity relationships that are necessary to go from one quantity to another. Thus, the tool served as a conceptual model (NRC, 2012) for understanding quantity relationships by: 1) defining what quantities one begins and ends with, and 2) what computations and quantity relationships are necessary to go from one quantity to another. Thus, the second research question is interested in understanding: ***How can a cognitive tool support students' sense-making around quantities and quantity relationships during chemical dimensional analysis?***

2.6 METHODS

2.6.1 *Context, Design, and Participants*

Twenty-three students in a general high-school chemistry class participated in the study. The students in the class were approximately three months into the class, and were learning how to engage in dimensional analysis to reason between the different quantity and quantity relationships in chemistry. To investigate students' learning, a basic qualitative design was used (Merriam, 2009). All students' written work was selected to understand the general trends in student thinking. One group of students were selected for in-depth observation during an activity. The selection of the group was based on a convenience sample. The students were from a high school chemistry class in a suburban school district. The school has an enrollment of 1,243 students, with a student to teacher ratio of 23:1. The demographic breakdown is as follows: 34.6% Caucasian, 24.9% Asian, 18.3% Black, 16.5% Hispanic, 3.8% Two Races, 1.0% American Indian, and 0.9% Pacific Islander.

This study is part of a larger study designed around NGSS implementation, and leverages a design-based implementation research (DBIR) perspective in its approach (Fishman, 2014). This study involved a research-practice partnership between university researchers, district-level science managers, science teachers (middle school science teachers from the Creston School District and high school science teachers from the Brentwood School District), and a non-profit science research organization. The partnership, over the course of three years, designed professional development sessions around the following goals: designing three-dimensional instruction (with a focus on the practices of modeling, explanation, and argumentation), implementing equitable discourse strategies, designing and making sense of student work around three-dimensional formative assessment, and incorporating phenomena in instructional units.

The high school chemistry teachers from the Brentwood School District came together during a five-day summer professional development institute, the partnership came together to design a series of lesson plans around the mole concept, a foundational concept and quantity in chemistry. In one of the lesson plans, the partnership designed the sequence of activities (as described in the next section) to support students in their reasoning in chemical dimensional analysis. They also developed a mathematical model (what will be referred to as the tool throughout this paper) that supported students to see the quantity and quantity relationships involved in chemical dimensional analysis (see figure 2.1).

2.6.2 *Sequence of Students' Activities*

Pre-laboratory assessment. Before the lab, the students completed a pre-assessment that asked them both algorithmic (#1) and conceptual (#2, #3) questions about dimensional analysis. The questions were as follows:

1) What is the mass of a sample of 7.33 * 10^{23} molecules of water?

2) Which of the following are true?

a. 6.02*10^{23} atoms = 12 g.

b. 6.02 *10^{23} atoms = 27 g.

c. Both are true.

d. Neither are true.

3) Fully explain your reasoning for your answer to question #2.

Laboratory exercise. The students then engaged in a laboratory exercise entitled, "Mole Buffet", using a tool (Figure 2.1) that helped them converts from macroscopic (e.g., mass) to microscopic (e.g., number of particles) quantities. This tool had three boxes for the different quantities that the students would be dealing with: mass of a sample, moles of a sample, and the number of particles in a sample. Furthermore, the arrows between the boxes showed the quantity relationships that would be needed to go between the different quantities.

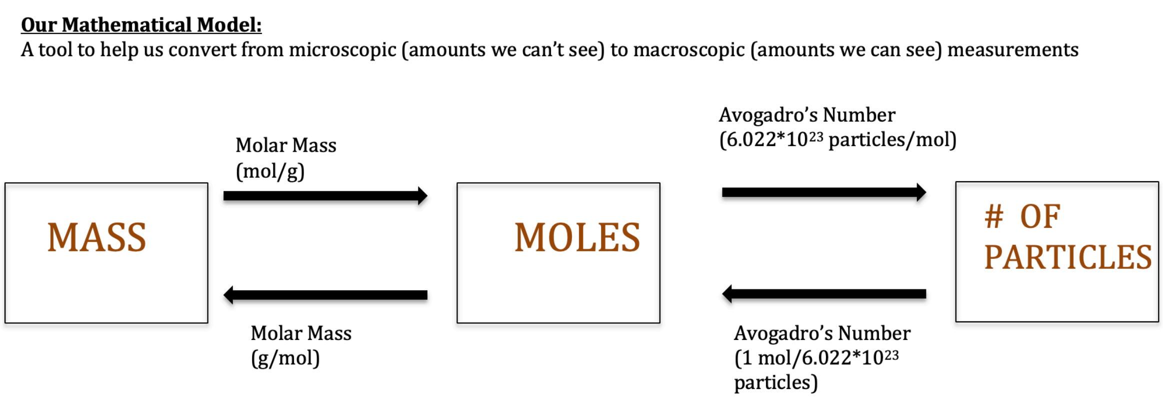


Figure 2.1 The tool that shows how the different quantities (in boxes) and quantity relationships (above/below the arrow) involved in chemical dimensional analysis.

The lab set-up consisted of 8 stations with specific chemical scenarios. In these stations, students had to figure out the mass, moles, or the number of particles at the specific stations, depending on the information being requested in the scenario. For example, the station in which the students were observed in had the following scenario:

> The formula for glass is SiO_2. How many silicon dioxide molecules are in this piece of glass?

Since the researcher was interested in the students' use of the tool, she selected a station in which the students would have to do a "two-step" conversion. In other words, the students would have to convert from mass to moles, and then from moles to number of particles. Thus, the students would be starting with one quantity, and then use two quantity relationships to obtain the desired quantity.

Post-laboratory assessment. After the lab, the students completed a post-assessment that asked them both algorithmic and conceptual questions about dimensional analysis. The questions were identical to the pre-laboratory assessment. The students were able to use the mathematical modeling tool that they had created prior to the lab to answer the questions.

2.6.3 *Data Collection*

There were two main sources of data for this study: video recordings and student work.

Video recordings. The video recordings were taken for an entire classroom period. This included the students' discussions as they were using the tool to make sense of chemical scenarios at the different stations.

Student Work. The student work collected includes the pre- and post-laboratory assessments collected during the lesson.

Data Analysis

Coding and analysis of pre- and post-assessments. The codes were developed through an iterative process, where the deductive codes were derived from the conceptual framework, and the inductive codes were derived from a grounded theory approach that reflects the themes emerging from the data (Strauss & Corbin, 1994).

Coding and analysis of video data. The talk between a group of five students around a lab station was transcribed. The segments of the talk that were specific to the students' use and reference of the tool were captured and are presented in excerpt chunks so that the reader can understand and appreciate the extent to which the tool guided students' thinking around dimensional analysis. The coding of the events were guided by the framework by Kozma (2000) in which students interactions with each other and with the tool were coded. Specifically, the following deductive themes were attended to in the analyses of the events: 1) how are students referencing or gesturing towards the tool in the course of their meaning making, 2) what are the social arrangements that are being leveraged to support their meaning making, and 3) in what ways are students attending to the conceptual and algorithmic aspects during their meaning making of chemical dimensional analysis.

2.7 RESULTS

2.7.1 *Research question 1: In what ways do students exhibit conceptual understandings of chemical dimensional analysis during problem solving*

The data presented in this section comes from students' pre-laboratory assessments (questions 2 and 3) to understand the conceptual ideas students can have about chemical dimensional analysis prior to understanding how to engage in the algorithmic aspects of dimensional analysis. Specifically, this question asks students to reason about whether a specific quantity statement (i.e., a statement that expresses a relationship between two quantities) is true, prior to them having the skills to algorithmically reason about the quantity statement. In the pre-assessment, students are given a set of quantity statements (e.g., $6.02*10^{23}$ atoms = 12 g) and asked which statements are true, and why or why not. These statements express relationships between two types of quantities (i.e., number of atoms and mass). An analogous cooking example would be the following: do 12 eggs = 16 ounces? A conceptual response to this statement could be: no, because one does not know the mass of an individual egg, as different -sized eggs have different masses, so one cannot absolutely conclude that 12 eggs is equal to 16 ounces. Analogously, students were asked to reason about a series of quantity statements with two types of quantities (i.e., number of atoms and mass) in which they could use a similar type of reasoning where they express that different types of atoms have different masses, so one cannot conclude the statement to be true or false.

Hence, this type of question is assessing whether students have a conceptual understanding of quantity statements, as students will be learning during the "mole buffet" activity how to implement dimensional analysis, in which they use the appropriate quantities and quantity relationships to go from the starting quantity to the desired quantity. Thus, when given the pre-assessment, the students cannot reason through this statement algorithmically, rather they must do so conceptually.

Student have multiple ways of expressing conceptual understandings of quantity statements in chemical dimensional analysis prior to having an algorithmic understanding

Overall, 70% or 16 of the 23 students were able to express one or more scientifically accurate chemical idea(s) that was appropriate to the scenario when they reasoned about the about the series of quantity statements that related the mass to the number of particles provided in the pre-assessment (question #2). Below are the themes that were uncovered in their written responses, which are not mutually exclusive.

Theme 1a: Element/substance identity matters

Sixty-one percent of the students (14) expressed that element identity matters for the scenario at hand. Some examples of this theme include: “we don't know what element either of the atoms are and 1 mole of any atom is a fixed number so depending on what atoms they are, they would be correct,” and “they both are true because you would have to know which element you are finding the mass of." In these types of statements, students are able to demonstrate that the type of atom will affect the mass of the sample. Thus, the students have an understanding that one cannot assert mass of fixed number of atoms, because this will vary based on the type of atom that is present in the scenario.

Theme 1b: Different elements have different masses

Forty-eight percent of the students (11) expressed that different elements have different masses for the scenario at hand. Some examples of this theme include: "due to different particle masses for different substances they are true to that substance" and “each element on the periodic table have different molar masses.” In these types of statement, it is implicit that students understand that element identity matters, and were able to demonstrate this while reasoning about the series of quantity statements provided. Thus, many students understand that not all atoms have the same mass; the identity of the atom is important in determining the cumulative mass of the atoms.

Theme 1c: Students gave examples of different elements/compounds with different masses

Of the 48% of the students (11) that expressed different elements have different masses, three of the students did so in the form of an example, showing how elements can have different masses when reasoning about the scenario at hand. Some examples include: “the mass of a mole of atoms can change depending on what sample of atoms you are testing. Ex a mole of carbon atoms is ~12 grams and a mole of aluminum atoms is 27 grams” and "depends on the element. H=1.00794, Pt=195.08, Ag=107.808."

If one were to ask someone the mass of 12 objects, one could not answer that question without knowing the mass of each of the objects. Analogously, in a chemical sample, not all atoms have the same mass, and the students were able to recruit this understanding of chemical identity to make sense of the quantity statements. Even though the atoms are sub-microsopic in nature and the students are unable to experience them in tangible ways, the students were able to demonstrate that one needed to know the identity of the elements in the sample prior to being able to make definitive quantitative statements (e.g., $6.02*10^{23}$ atoms = 12 g).

The students in the pre-laboratory assessment were asked to reason about a set of statements that related the number of atoms to the mass in a sample. Through the themes observed above, it is evident that a majority of the students were able to reason about a quantity statement in conceptual ways, prior to being able to reason about them in algorithmic ways. In other words, students generally can reason about a quantity statement prior to being able to set one up using the appropriate quantities and quantity relationships via chemical dimensional analysis.

2.7.2 *Research question 2: How can a cognitive tool support students' sense-making around quantities and quantity relationships in chemical dimensional analysis?*

The first part of data from this comes from the video data from five students as they are making sense of dimensional analysis in the context of a scenario presented during a laboratory exercise (mole buffet activity). The findings here demonstrate the ways in which students can make sense with a tool to support their emerging understanding of chemical dimensional analysis (finding 2). The second part of the data comes from evaluating students' pre- and post-assessments. The findings here demonstrate the patterns observed in the ways that the students expressed the various quantities and quantity relationships involved in chemical dimensional analysis (findings 3a and 3b).

Part 1: Students' sense-making with a cognitive tool around chemical dimensional analysis

Finding 2: Students were able to resolve confusion between quantities and quantity relationships involved in chemical dimensional analysis in both conceptual and algorithmic ways

Initially Shawn makes two sets of claims, as shown in table 2.1. First, in line 4, Shawn expresses the claim that "moles is the number of molecules" (conceptual statement); he expresses the same claim in line 17. Second, in lines 19 and 20, he claims that one can divide the molar mass to get the molecules (algorithmic statement). Through the social and material interactions around the tool, Shawn and the group are resolving two sets of initial claims: whether moles are molecules (conceptual statement) and how to compute the number of molecules (algorithmic statement). These interactions are critical in supporting Shawn and the group to resolve these two claims through a process of collaboration and convergence. Roschelle (1992) discusses how groups of two or more people can coordinate the construction of concepts so that they can converge on a specific, shared conceptual understanding. The process of collaborative convergence involves cycle(s) of displaying, monitoring, and repairing shared meanings. Thus, the process of conversational and material interactions can support the construction of meanings incrementally and across refinements of thinking. The cycles of displaying, monitoring, and repairing shared meanings for each of Shawn's claims are shown in table 2.2.

Conceptual claim: Shawn claims in line 17 that moles are molecules, which is confirmed by Edward, and the two of them proceed through the activity with this assertion. Through this part of the conversation, Shawn and Edward are displaying a shared meaning that moles are molecules. But as they compute the number of moles, they end up with a number less than one (.528). This leads Shawn to claim that this doesn't make sense (line 24), and to ask Chris (lines 28-31) whether moles are molecules, with Chris responding that they are not and that "moles is a mole." When Shawn states that there are .528 moles, and then subsequently that this doesn't make sense, he is realizing that one cannot have less than one molecule (that is, if his original claim that moles are the number of molecules is true). This then prompts Shawn to ask Chris whether moles are molecules. Shawn and Chris then engage in repairing the original shared meaning from "moles are molecules" to "moles are moles". In Shawn's claim, "wait, that doesn't make sense", he is monitoring that the shared understanding no longer applies, and thus "breaks" the confirmation of the shared understanding, and launches into repairing it with Chris. Through his conversation with Chris, they are able to resolve the difference between these two sets of quantities. In other words, moles are not molecules.

Algorithmic claim: Shawn claims in line 19 that in order to compute the number of molecules, one can divide the mass by the molar mass, which is then agreed to by Edward. Through this part of the conversation, Shawn and Edward are displaying a shared meaning of the computations needed to arrive at the number of molecules. Shawn, after resolving the distinction between moles and molecules, is then prompted to ask how one finds the number of molecules (line 32). At this point, multiple interactions start to emerge. Edward begins to say one multiplies (line 33), Jessica shows Shawn a relevant part of the tool (line 34), Chris says that you can do a conversion to get to the number of molecules (line 35), and then Edward and Shawn construct the appropriate operations, quantities, and quantity relationships need to take place to arrive at the number of molecules (lines 36-44). Through these series of interactions, Shawn, Chris, Edward, and Jessica are engaging in the process of monitoring and repairing the original shared meaning of how to compute the number of molecules. There is multi-faceted coordination amongst Shawn, Edward, Chris, Edward, the tool, and a calculator where they collectively reference the tool and discuss the computations needed to convert from moles to number of molecules.

Through collaborative convergence, the students engaged in displaying, monitoring, and repairing their shared understandings. This occurred for two specific understandings: 1) the students' differentiation of moles and molecules, and 2) the students' understanding of the appropriate operations, quantities, and quantity relationships needed to convert from moles to molecules. It is important to note that the cycles of displaying, monitoring, and repairing for each claim are not independent; rather they are interdependent. The algorithmic repair did not occur until the conceptual repair. The conceptual repair (i.e., moles are not molecules) prompted the students to realize that the original set of computations proposed for the number of molecules was not correct, and to then set-up the appropriate computations. Thus, the cycles of convergence can be interdependent, where the conceptual understanding can drive the algorithmic understanding.

Table 2.1 Excerpt from one group of students' sense-making around a chemical scenario using the tool.

Line	Student Utterances and Actions
[1]	Shawn: How many silicon dioxide molecules are in that piece of glass. (1) (2)
	(1) Shawn is reading the lab work sheet
	(2) Edward walks towards scale
[2]	Edward: (1) It's 31.74 grams. (2)
	(1) Edward comes back to lab station and is writing on his sheet of paper
	(2) Shawn writes this number down on his sheet of paper
[3]	Edward: So, then we find the molar mass of silicon dioxide.
[4]	Shawn: Yeah, and moles is the number of molecules. (1) (2) (3) (4)
	(1) Edward walks away from lab station
	(2) Shawn walks away from lab station with his calculator
	(3) Edward comes back and writes something down on his paper
	(4) Shawn comes back with his calculator
[5]	Shawn: 60.0843.
[6]	Edward: 60.0843 grams. Alright, so then. So, then 31.74 divided by 60.0843. This should
[7]	give us the... how many moles it is. Right?
[8]	Shawn: Yeah
[9]	Edward: And then we can divide the molar mass by the number of moles. It should get
[10]	how many...
[11]	Shawn: What is it the moles? The amount of molecules though
[12]	Edward: Wait hold on. So, we trying to find is the number of particles, right?
[13]	Shawn: No, we are trying to find the number of molecules
[14]	Edward: But, yeah, but. Particle is -
[15]	Shawn: Particles are different from molecules
[16]	Edward: I thought... A mole -
[17]	Shawn: Okay, the moles are actually the number of molecules (1)
	(1) Points to tool
[18]	Edward: Got it.
[19]	Shawn: So, basically we just gotta divide by, we just gotta divide the mass by the molar
[20]	mass and then we get it.
[21]	Edward: Okay
[22]	Shawn: So, 31.74 (1)(2) divided by 60.0843 equals point 5-2-8.
	(1) puts it in his calculator
	(2) reads from his calculator
[23]	Edward: Point 5-2-8 moles
[24]	Shawn: Wait, that doesn't make sense
[25]	Edward: And then we have moles, right
[26]	Shawn: Moles? Hold on.
[27]	Edward: Yeah, but then we can, then we can, further, uh, do the conversion
[28]	Shawn: Chris, moles are the number of molecules, right? (1)
	(1) Shawn asks a student from a nearby group

[29] Chris: Uh, no.
[30] Shawn: What's -
[31] Chris: Moles is a mole.
[32] Shawn: So, how do we find the number of molecules?
[33] Edward: What we can do is multiply -
[34] Jessica: Yeah (1)
(1) Brings her tool closer to Shawn and points at it
[35] Chris: You can do the conversion
[36] Edward: What we can do is multiply this by how many moles the glass is.
[37] Shawn: Yeah
[38] Edward: Times
[39] Shawn: Times six point
[40] Edward: Six point zero two times ten to the twenty-third (1)
(1) Sean enters the calculations into calculator
[41] Shawn: Three point one-eight (1)
(1) Reads from his calculator
[42] Edward: Three point one-eight. Three point one-eight times ten to the twenty-third.
[43] That's how many silicon dioxide molecules there are.
[44] Shawn: Yes.

Table 2.2 The cycle of displaying, monitoring, and repairing that the students engaged as they achieved collaborative convergence. The text in red represents the cycle for the conceptual claim and the text in blue represents the cycle for the algorithmic claim.

Act	Students' Utterances and Actions
Displaying	Shawn (Line 17): Okay, the moles are actually the number of molecules (1) (1) Point to tool Edward (Line 18): Got it Shawn (Line 19): So, basically we just gotta divide by, we just gotta divide the mass by the molar mass and then we get it Edward (Line 20): Okay
Monitoring & Repairing (conceptual differentiation of mole and molecules)	Shawn (Line 24): Wait, that doesn't make sense Edward (Line 25): And then we have moles, right? Shawn (Line 26): Moles? Hold on. Edward (Line 27): Yeah, but then we can, then we can, further, uh, do the conversion Shawn (Line 28): Chris, moles are the number of molecules, right? (1) (1) Shawn asks a student from a nearby group Chris (Line 29): Uh, no Shawn (Line 30): What's – Chris (Line 31): Moles is a mole
Monitoring & Repairing (algorithmic computation of molecules)	Shawn (Line 32): So, how do we find the number of molecules? Edward (Line 33): What we do is multiply – Jessica (Line 34): Yeah (1) (1) Brings her tool closer to Shawn and points at it Chris (Line 35): You can do the conversion Edward (Line 36): What you can do it multiply this (1) by how many moles the glass is (1) Points to the tool Shawn (Line 37): Yeah Edward (Line 38): Times Shawn (Line 39): Times six point Edward (Line 40): Six point zero times ten to the twenty-third (1) (1) Sean enters the calculations into calculator Shawn (Line 41): Three point one-eight (1) (1) Reads from calculator Edward (Line 42): Three point one-eight. Three point one-eight times ten to the twenty-third. That's how many silicon dioxide molecules Edward (Line 43): there are Shawn (Line 44): Yes

<u>Part 2: Students' understanding of quantities and quantity relationships in chemical dimensional analysis</u>

Finding 3a: Students became more fluent in presenting the correct calculations for the molar mass of a substance

One of the fundamental quantity relationships that is needed to engage in chemical dimensional analysis is to be able to compute the molar mass of a substance. In order to do so, one needs to be able to identify all of the elements in a substance and sum their corresponding atomic masses. In the pre-assessment, 48% of the students presented calculations (whether they were incorrect or correct) for the molar mass, and 30% of the students were able to obtain the correct molar mass for the substance. In the post-assessment, 70% of the presented calculations (whether they were incorrect or correct) for the molar mass, and 83% of the students were able to obtain the correct molar mass for the substance. Given that more students have the correct molar mass than are presenting their calculations in the post-assessment, this may be because the students felt more comfortable calculating the molar mass on their calculators without physically representing it on paper and/or the molar mass for the substance (i.e., H_2O) in the assessment was relatively straightforward to calculate, thus the need for physical representation was not necessary.

The pre- and post-assessment data from above shows that there was an increase in both the percentage of students who presented their calculations (22% increase) and had the correct ones from the pre- to the post-assessment (53% increase). This may be because the activity enabled students more opportunities in identifying the atoms in the substances and their masses, and then summing them up to obtain the molar masses of the various substances. This is an important aspect of chemical dimensional analysis, as being able to identify all of the atoms in a sample (both in number and chemical identity) are critical to the accurate computation of the molar mass.

Finding 3b: Students became proficient in identifying and setting-up the appropriate quantities and quantity relationships in chemical dimensional analysis

The problem posed to the students required them to do a “two-step” calculation, where they needed to identify the starting quantity and use two sets of quantity relationships to be able to convert from mass to number of particles. In the example given in the pre- and post-assessments, the correct answer would require that they start with the number of molecules (quantity), which then needed to be multiplied by the number of molecules in a mole (quantity relationship #1) and then be multiplied by the molar mass (quantity relationship #2) (see figure 2.2).

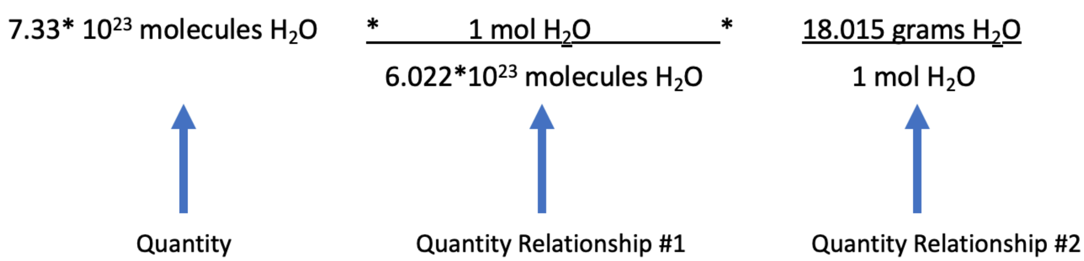
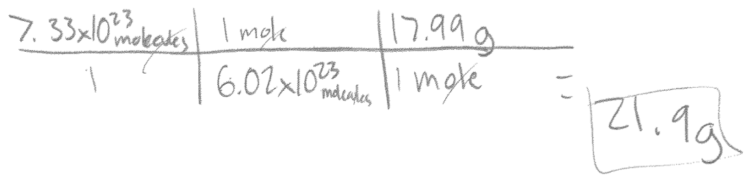


Figure 2.2 The appropriate quantity and quantity relationships that need to be set-up in the scenario presented in the post-laboratory assessment.

To assess whether the students were representing an entity as a quantity relationship, the following features were coded their responses: 1) the presence of units in the numerator and denominator, or 2) the use of an organizational scheme that showed that the entity was not just a number or quantity, but rather a *quantity relationship*. Figure 2.3 shows an example of these two types of responses, respectively.

#1



#2

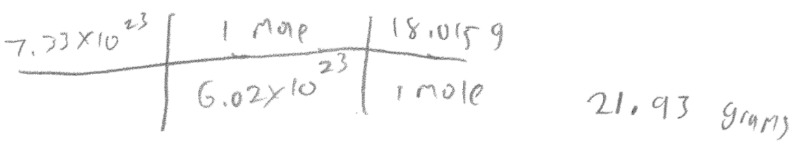


Figure 2.3 Students' set-up of quantities and quantity relationships to the scenario in the post-laboratory assessment. In the first example, a student displays units both in the numerator and denominator. In the second example, a student does not consistently display units both in the numerator and denominator, but uses an organizational scheme that showed that the entity was not just a number or quantity.

In the pre-assessment, 17% of the students performed a "one-step" calculation, where they had a quantity multiplied by a quantity relationship, whereas 0% of the students had performed a "two-step" calculation, where they had a quantity multiplied by two quantity relationships. In the post-assessment, 4% of the students performed a "one-step" calculation, whereas 87% of the students had performed a "two-step" calculation. Of these 87%, 83% had the correct set-up; in other words, they had identified the appropriate quantities and quantity relationships. Thus, in comparing students' performance in the pre- and post-assessments, students were better able to express the quantities and quantity relationships that were required to solve the problem in the assessment. Furthermore, implicit in this task, students were able to represent a quantity relationship such that it showed that it was a ratio of two quantities. This was evidenced by their use of units in the numerator and denominator and/or their use of the organizational scheme, as shown in figure 2.3.

Through the analysis of the students' post-laboratory assessments after the laboratory exercise, the students became more able to identify and compute the appropriate quantities and quantity relationships in chemical dimensional analysis, while using the tool. Thus, the students used the tool to both support them in their understanding around the different aspects (i.e., quantities and quantity relationships) of chemical dimensional analysis and to become proficient in using the tool in the appropriate contexts, as evidenced by the data in findings 3a and 3b.

2.8 Conclusions and Implications

The current study investigated: 1) how students exhibited conceptual understandings of and 2) the ways in which a tool can support students' sense-making around quantities and quantity relationships of chemical dimensional analysis. For the first question, this study showed that students can reason about quantities and quantity relationships using their conceptual knowledge in chemistry. The research literature has often shown the converse, where students can reason algorithmically but not conceptually around specific chemical ideas (Nurrenbern and Pickering (1987); Sanger, 2005; Cracolice, Deming, and Ehlert (2008)). Thus, when given the appropriate questions, students can reason about quantity statements prior to having the understanding of the quantities and quantity relationships needed to perform them. Specifically, the majority of the students were able to bring the following conceptual ideas to their reasoning about quantity statements: a) element/substance identity matters and/or b) different elements have different masses. For example, when one is asked how much does a dozen items weigh? One cannot answer that question without knowing the mass of each of the items. Analogously, one cannot know the mass of a chemical sample without knowing which elements make up the sample. The majority of the students were able to apply this insight to the quantity statements, even though they were not able to set-up the appropriate quantity and quantity relationships in the pre-assessments. Thus, students can reason about quantity statements in conceptual ways, prior to having the ability to put together these statements together through the act of chemical dimensional analysis.

For the second question, this study demonstrates how a tool can support students' sense-making around dimensional analysis. In the case provided, the tool served as a mediating object that made visible the quantities and quantity relationships involved in dimensional analysis. This is evident from the exchanges between Edward, Shawn, Chris, and Jennifer. Their conversation is evidence of how social and material interactions are important in supporting students' sense-making around dimensional analysis. Through their discussion and reference of the tool, they are able to resolve the difference between moles and molecules, and are able to understand the appropriate quantity relationship to go from moles to molecules. This exchange is critical as it allows the students to be able to reason amongst themselves through an alternate conception (i.e., moles are molecules) that occurs commonly in the science class. Furthermore, the social interactions with the tool guided them to work through conceptual and computational aspects of chemical dimensional analysis. Additionally, in the post-assessment, 83% of the students were able to set-up the appropriate quantities and quantity relationships in the post-assessment. The students through tool-mediated activity had learned how to set-up the algorithm which involved the appropriate quantities and quantity relationships. This is an essential for chemical dimensional analysis, as students are learning how to navigate between macroscopic and sub-microscopic quantities. The learning of chemical dimensional analysis occurred through both socially constructed and internalized processes; both an active individual and environment exist, with the third factor of mediated activity (Cole & Wertsch, 1996).

This study was not meant to demonstrate an exhaustive list of all possible conceptual understandings of dimensional analysis, nor a list of all the ways in which students can engage with a tool to make sense around dimensional analysis. Rather, it was meant to demonstrate the possibilities of conceptual thinking around in algorithmic contexts and how tools can support students to become more fluent in reasoning about quantities and quantity relationships. Based on the findings, there are three recommendations that can help move the conversation move forward on mathematical thinking in scientific contexts.

First, learning environments must attend both to students' conceptual and algorithmic understandings. Often, assessments focus on the latter type of understanding, thus ignoring students' conceptual understanding of the subject matter (NRC, 2012). In fact, prior research has shown that not only are algorithmic understandings privileged but that they can mask conceptual understandings in advanced undergraduate physics contexts (McDermott, 2015). While an understanding of the computational or procedural aspects of an algorithm is important, it is just as critical to attend to students' conceptual understandings and sense-making – even in the area of computation. Furthermore, these two types of understandings are not independent of one another; rather they are different representations of a specific conceptual topic. Thus, it is important to attend to both the conceptual and algorithmic aspects when engaging in problem solving. This can occur in ways where students are asked to reflect on the conceptual and algorithmic aspects separately and together.

Second, tools need to be designed in ways that support students in their mathematical sense-making in science. There are multiple ways in which students make meaning using mathematical thinking such as using equations and developing quantitative representations around scientific problems and phenomena. Thus, the tool should be specific to the desired objectives (e.g., making visible appropriate relationships between variables in equations, fostering understanding of place value in measurement, understanding changes in systems using ratios, etc.). Through tool use, students can draw on specific aspects of a representation to support their conceptual understandings (Sherin, 2001). Furthermore, a tool can be designed to foster multiple zones of proximal development, where participants can navigate the tools in a manner that is appropriate to their level of understanding and rate (Brown & Campione, 1998). As this research shows, an emergent property of the tool can be that it supports the integration of both conceptual and algorithmic understandings. For example, although not all students were able to be observed at all stations in the laboratory exercise, the researcher overheard the phrase "there are no naked numbers" come up during the course of the students' discussions. This statement has conceptual value because it highlights an important aspect of quantities in science: qualitative identification. In science, one encounters many numbers, but without a label they do not have any meaning. Although, the conceptual expressions via activity will vary in degree and quantity between students, a mediating object in activity system can support students' abilities to make sense of chemical ideas and the emergence of a variety of conceptual expressions.

Third, activity systems should be designed with opportunities for both sense-making and the development of representational competence around the symbolic level of representation in chemistry. In the present research, students were able to engage with a tool to support them in their reasoning in chemical dimensional analysis. This tool not only supported students' in sense-making in various chemical scenarios (left triangle in figure 2.4), but it also supported them in becoming more proficient in chemical dimensional analysis (right triangle in figure 2.4). Being able to use chemical dimensional analysis flexibly is an important form of reasoning within the chemistry triplet (Talanquer, 2011). It is also part of a broader suite of skills needed to reason about chemical scenarios using all aspects of the different representational aspects of chemistry (Johnstone, 1993; Stieff, 2011).

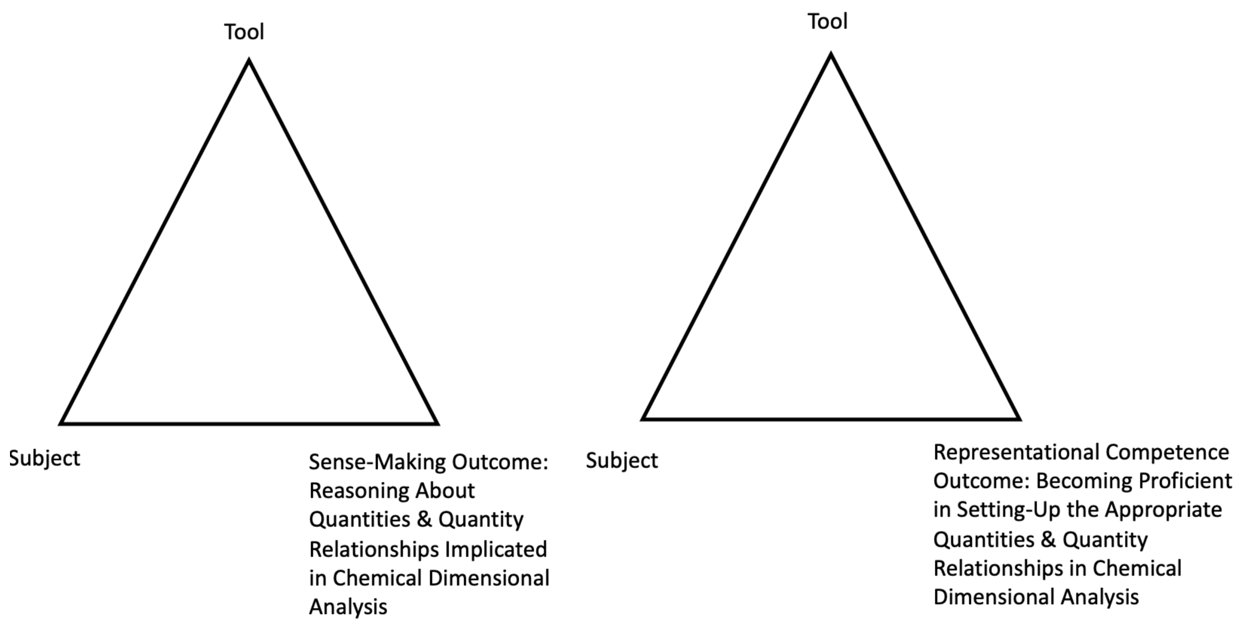


Figure 2.4 Schematic demonstrating how a tool serves as a mediating object to support both sense-making (reasoning about quantities & quantity relationships in chemical dimensional analysis) and representational competence (proficiency in setting-up the appropriate quantities & quantity relationships in chemical dimensional analysis).

Dierks, Weninger, and Herron (1985) define a quantity "as an attribute of a phenomenon or of a body, which is susceptible to qualitative identification and quantitative determination." Thus, the two components of qualitative identification and quantitative determination can be broadly applied to scientific phenomena under investigation, and can empower students to visualize, predict, and solve problems when making sense of phenomena using the practice of mathematical thinking. And with the recommendations proposed above, mathematical thinking can become accessible, appropriate, and interconnected to scientific sense-making.

Chapter 3. USING CONCEPTUAL SKETCHES TO MAKE SENSE OF PHENOMENA AT THE SUB-MICROSCOPIC LEVEL

The National Research Council put forth a book entitled, Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering (NRC, 2012). In this book, they identify the goals of Discipline-Based Education Research (DBER), which include to: "understand how people learn the concepts, practices, and ways of thinking of science and engineering" and "understand the nature and development of expertise in a discipline" (p. 2). In the book they identify what this looks like in the various STEM disciplines. In chemistry, they call out the chemistry education framework as providing a structure for chemistry education research and in shaping the concepts, practices, and development of expertise in chemistry.

One foundational aspect of chemical reasoning is to be able to connect the macroscopic observations (e.g., color, solubility) to the sub-microscopic level of representation (e.g. structure and particulate nature of matter) (NRC, 2012). The present research focuses on how students can be supported to connect the macroscopic and the sub-microscopic levels of representation in chemistry. Specifically, it will explore how conceptual sketching can support students' ability to connect a macroscopic observation to their conceptual understanding of a sub-microscopic interaction, namely intermolecular forces. The concept of intermolecular forces is addressed in introductory chemistry courses at the undergraduate level and is a concept in which students need additional supports (Cooper, Williams and Underwood, 2015).

This chapter will first talk about the chemistry education research framework, and the different aspects of chemical thinking that are implicated for the present study. Specifically, attending to the macroscopic and sub-microscopic levels of representation. Second, it will look at the role of educational activities in supporting students in connecting these two levels of representation. It will talk about the role that conceptual modeling plays in this process, leveraging perspectives from the research literature in science and chemistry contexts. Third, it will talk about a specific form of modeling, conceptual sketching, that students engage in chemistry classes. Lastly, it will situate the present research study, chemical concepts under investigation, and research questions.

3.1 CHEMISTRY EDUCATION FRAMEWORK

In the 1960s, there were curricula developed (ChemStudy and Chemical Bond Approach) in response to the perception that chemistry was being taught only at the macroscopic level or observational level (NRC, 2012). The new curricula were aimed at supporting students to develop a deeper understanding of chemical principles and atomic molecular theory (NRC, 2012). These curricula are in line with Johnstone's (1993) foundational framework which identifies the three critical components of chemistry knowledge: 1) the macroscopic or observational level, 2) the sub-microscopic or particulate level interactions, and 3) the symbolic level which includes the numbers, letters, and other symbols used to communicate chemistry knowledge.

When engaging in chemical reasoning, it is critical for students to be able to use their understanding of the behavior of particles (i.e., the sub-microscopic level) to make sense of an observable event or phenomenon (i.e., macroscopic level) (Johnstone, 1993). For example, one can take the example of what is happening to water as it's boiling. In this phenomenon, the liquid is changing phase from liquid to gas (macroscopic or observational level). To understand why this is happening, one needs to appeal to the sub-microscopic level. At the sub-microscopic level, the water molecules are gaining kinetic energy when heat is being added, and as a consequence, they are becoming farther apart. As the heat is being added over time, this then leads to the water to change phase from liquid to gas. This last statement connects the sub-microscopic level to the macroscopic level. In a chemistry context, the sub-microscopic level is also known to be the explanatory or causal account of a chemical phenomenon because it conceptually connects the behavior of the particles that lead to the observation (Talanquer, 2011). In broader science contexts, causal scientific explanations provide the explanatory power for a scientific phenomenon (Braaten and Windschitl, 2011; Salmon, 1978).

3.2 MODELING ACTIVITIES IN CHEMISTRY

In the field of chemistry, students are frequently inferring the behavior of particle-level interactions (sub-microscopic level) to make sense of an observable event or phenomenon (macroscopic level) (Johnstone, 1993). To succeed in connecting these levels of representation in chemistry, activity systems need to be developed that mediate understandings between what can (macro) and cannot be seen (sub-micro); in other words, how can the particulate based interactions be leveraged to can be used to explain chemical events that are observed at the macroscopic level. Activities that exhibit model-based reasoning as a pedagogical strategy can help students understand these relationships; specifically, how the sub-microscopic components and processes give rise to the macroscopic (or observable) phenomenon.

There have been many calls for model-based reasoning both within chemistry education (Harrison and Treagust, 1996; Snir, Smith, and Raz, 2003) and broadly in science education (Lehrer, 2009; Schwarz, et al., 2009; Windschitl, Thompson, and Braaten, 2008; White and

Frederickson, 1998). From the perspective of chemistry, there is a need for students to understand that there are different types of models used in chemical reasoning, which include but are not limited to analogical models (e.g., ball-and-stick to represent chemicals), chemical formulas, and mathematical models. Treagust points out that it is important for students to understand that there can be multiple models used to make sense of a phenomenon, and that these models are not one-to-one correspondences with reality, rather they are meant to serve as a basis for testing and developing ideas. Thus, instruction should make explicit the shared and unshared attributes of a phenomena-based model. Snir also echoes these perspectives by highlighting the importance for students to understand that models can be isomporphic but can use different visual or conceptual tools to depict different aspects of reality. Furthermore, Snir talks about the importance of helping students use explanatory models as a metaconcept in science, where students are also thinking about a model in terms of the theoretical entities and relations in the model and that they are used to explain and predict the outcomes in phenomena. But, models are not just about systems of representation; using models is an activity whereby students' can develop and exercise epistemically based practices in science (Lehrer, 2009; Windschitl, Thompson, and Braaten, 2008). Windschitl et al., (2008) describe how the language and activities in a science classroom can support the epistemic features of science knowledge, that emphasizes that models that are testable, revisable, explanatory, conjectural, and generative in nature. Model-based activities can help support students in organizing what they know and want to know, which can lead to the deployment of other epistemic activities such as generating and testing hypotheses, seeking appropriate evidence, and constructing arguments (Windschitl, Thompson, and Braaten, 2008).

Thus, when developing activities for chemical inquiry, there are two critical ways to attend to models, which are not mutually exclusive. First, models can be understood as different systems of representation that can be used to make sense of a scientific concepts. This means that one may be engaging in different forms of representation (e.g., equations, diagrams, physical models) to describe a chemical idea or phenomenon. Second, modeling can be understood as an epistemic practice, which often recruits other practices such as explanations and argumentation, where one is proposing a causal account for an unobservable process, by representing a set of relationships between the substances in a system, and using it to generate insights and/or predictions about a phenomenon (Windschitl, et al., 2008). In the first case, the term “model” is a noun, whereas in the second case, it is a verb. However, these two perspectives on modeling are aligned and complementary. In chemical reasoning, the three levels of representation each have a form of representation (model as a noun) which is based on the norms and conventions of the scientific classroom and/or community, and it is the causal connection between these levels that constitutes an explanatory account for a phenomenon (model as a verb).

3.3 CONCEPTUAL SKETCHING IN CHEMISTRY

In chemistry, modeling can help students revise their mental models of scientific concepts, where mental models are “a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning” (p. 48, Vosnaidou, 1994). Often in chemistry, students first reason about the observational or the macroscopic level of the phenomena and then transition to reasoning about the mechanistic accounts, or the sub-microscopic interactions that are occurring that result in the underlying phenomenon. One common way for students to make sense of the mechanistic account is to engage in sketching the sub-microscopic interactions (Cooper, Stieff, and DeSutter, 2017). In this case, sketching is not an isolated task, rather it is meant to further students' understanding of the sub-microscopic level by enabling them to model the substances and the relationships between them to explain and/or predict the outcomes in a phenomenon. This has been empirically shown in the college CLUE (Chemistry, Life, the Universe, and Everything) curriculum, which emphasized the importance of sketching in making sense of chemical phenomena. Furthermore, the students who engaged in sketches were better able to convey spatial information about intermolecular forces. Thus, the sketching enabled them to convey their thinking about specific aspects of the phenomena visible.

The cognitive benefits of sketching have also been shown with the high-school level Connected Chemistry Curriculum (CCC) (Stieff, 2011). In this particular curriculum, students used a computer-based guided inquiry that showed simulations that emphasized how sub-microscopic interactions related to macroscopic concepts. Studies have shown that students frequently and incorrectly use representations and characteristics of macroscopic phenomena when asked about the sub-microscopic level (Harrison and Treagust, 1996). In the CCC, the students engaged in a series of simulations activities around various chemical concepts that emphasized the linkage between macroscopic and sub-microscopic levels of representation. Students were asked to engage in three types of sketches: predictive, observational, and reflectional. These sketches occurred in this sequence so that students had an opportunity to convey their initial understandings (predictive), document new understandings from a simulation (observational), and then revise and or make new predictions about a new chemical system (reflection). These different sketches allowed students to engage in the various epistemic features in modeling (Windschitl, Thompson, and Braaten, 2008). Furthermore, students who used the CCC (as compared to a non-simulation based curriculum) depicted chemical phenomena from a sub-microscopic level of representation more frequently and were more likely to indicate dynamic molecular motion, at the sub-microscopic level. Thus, the simulation provided students linkages between observable and non-observable events. These studies collectively show that students who engaged in sketching were more likely to undergo conceptual change (Cooper, Stieff, and DeSutter, 2017). In other words, the sketching afforded students the ability to revise their mental models, by enabling them to make visible and interrogate the sub-microscopic level of representation (e.g., what are the atoms doing, how are they interacting). A mediating object, such as a conceptual sketch, can support students in their meaning-making of a chemical phenomenon by supporting them to reflect on the particles and particle-level interactions that may be occurring. As students reflect on and revise their mental models, it makes their ideas accessible, revisable, and communicable to themselves and others.

3.4 PRESENT STUDY AND RESEARCH QUESTIONS

In chemistry, it is important to provide students with opportunities to model between the different levels of representation. This can involve lab investigations and/or reasoning about everyday phenomena, where students are students are prompted to use multiple, linked presentations in these contexts (Kozma, 2003). Kozma et al., (2000) studied the language, tools, and representations between chemists in a lab setting. In this study, they found that scientists collectively used these resources to: express their research goals (in terms of molecular structures of compounds), reason about physical processes needed to synthesize the compounds, and to verify the underlying composition of the synthesized compound. In the conversations between the chemists, the scientists moved flexibly from one form of representation to another. For example, in their dialog, the chemists gestured to chemical equations and structures on a diagram as they were talking about how the reaction was occurring at the sub-microscopic level. This is an example of the chemists reasoning about and making connections between the symbolic representations (i.e., chemical equations and structures) and the sub-microscopic representation (i.e., description of how molecules are behaving in the reaction). Specifically, they are engaging in a form of conceptual modeling by describing how unobservable entities are behaving through the use of verbal explanations and physical diagrams. It is important to note that scientists, in addition to using physical diagrams, also leverage gestures, printed materials to coordinate their sense-making around a phenomenon (Ochs, Gonzales and Jacoby, 1996).

Unlike scientists, students do not have the experience to reason flexibly with multiple representations, and therefore, need additional supports to aid them in this process. One way to do so is through the development of a record of thinking (Windschitl, et al., 2012), like scientists do as they engage in reasoning. This type of artifact can surface a wide range of student ideas, and engage their facets of thinking (Minstrell, 1989). Where the facets of thinking are viewed as operational ideas or resources that students are bringing to reason about the task, not conceptual errors or misconceptions. Also, this type of artifact can also prompt students to think about how and which sub-microscopic level components to represent to further their understanding of a chemical phenomenon. As students engage in their model, prompts can be embedded that enable them to connect the sub-microscopic and macroscopic levels. These prompts can also lead to questions about how the model does/does not help make the connections between the macro and sub- micro levels of representation, what revisions are needed to the model, and the limitations of the model (Windschitl, Thompson, and Braaten, 2008). Many instructional interventions in chemistry have focused on connecting students' macroscopic understandings to the sub-microscopic understandings through the use of material means such as sketching and simulations. These material means not only afford students the ability to visualize and make sense of unobservable entities, but through this process, the material itself has now inherited a functional form that aids in student reasoning, whereby the "intelligence" is distributed between the subject(s) and the material tools (Pea, 2004). In a study by Stevens and Hall (1998), people can "learn to see with and through their inscriptions," where these inscriptions include graphs, diagrams, and models. And through this visual interaction with the inscriptions, people can demonstrate the relevant dimensions of their work. Thus, the students' use of the material tools (i.e., conceptual sketch) serves as a fundamental part of the meaning making and it is through the visual interaction with the inscriptions that they can start to see and demonstrate the relevant dimensions of the chemical phenomena.

The present study is investigating the role that conceptual sketches can play in supporting students' understanding of intermolecular forces. Prior research has shown that students do not have a consistent understanding of intermolecular forces across contexts (Cooper, Williams, and Underwood, 2015). When asked to draw or write about intermolecular forces, students struggle with identifying where they exist between molecules (Cooper, Williams and Underwood, 2015). The present study asked students to reason about a chemical phenomenon, in which the students had to recruit their understanding of intermolecular forces. There were two comparison groups of students in this study: one that engages in conceptual sketching and another group that does not. The conceptual sketches included prompts to guide students in their thinking about intermolecular forces. The following research questions were addressed in this study: 1) in what ways do conceptual sketches affect students' explanations of chemical events at the sub-microscopic level, and 2) how do students represent the interactions in a chemical phenomenon in their sketches as compared to their causal explanations?

3.5 Methods

3.5.1 *Context, Design, and Participants*

The present study takes place in an undergraduate general chemistry course in the Pacific Northwest region of the United States. The university has an enrollment of approximately 5,000 undergraduate students, of which 28% of these students are enrolled in STEM programs. The demographic breakdown is as follows: 36% Caucasian, 30% Asian, 10% Hispanic or Latino, 7% Black or African American, 6% Two or more Races, 2% Did not Indicate Ethnicity, 1.0% Native Hawaiian or Pacific Islander, and <1% American Native or Alaska Native. There were approximately 120 students who participated in the broader study. The study occurred during the second quarter (out of three quarters) of the general chemistry sequence, where the focus is on topics such as energy, enthalpy, thermochemistry, gas laws, properties of solutions, solids, entropy, free energy, spontaneity, and organic chemistry. The broader study was conducted over two years. In the first year, the students were given three chemical phenomena (please see Appendix A) to reason about without the opportunity to sketch their ideas (non-sketching group). In the second year, the students were given the same three chemical phenomena to reason about with an artifact (please see Appendix B) that gave them the opportunity to sketch their ideas and that also embedded specific chemical concepts (sketching group). The present study will focus on the results from chemical phenomenon #2 that involves the concepts of intermolecular forces (please see next section for details). One-hundred students participated in the activities for the non-sketching group, and seventy-five students did so in the sketching group.

The study leverages a design-based research approach to its implementation (Cobb, et al., 2003). In the first year, the students did not engage in conceptual sketching. A preliminary analysis of the student work showed that a high percentage of the students were not able to identify the sub-microscopic entities involved in the phenomena. Given that this was an important outcome, the researcher and instructor-researcher implemented conceptual sketching into the next iteration of the intervention as a means for the students to make visible the sub-microscopic entities involved in the phenomena. Thus, the intended outcome became the basis for the next cycle of inquiry (Cobb, et al., 2003).

3.5.2 *Sequence of Activities*

The students were presented three phenomena over the course of the quarter and asked to reason about what was occurring at the macroscopic and sub-microscopic levels. The phenomena asked them to explain the following events: 1) what happens when a balloon is inflated, 2) why does water “climb” up the walls of an inverted test tube, and 3) what happens when an egg with a semi-permeable membrane is placed in a hypertonic solution. For the last two phenomena, the students also viewed a video in which they observed the events occur. They were given the following questions for each phenomenon:

> *Macroscopic level:* How would you describe this process at the macroscopic (e.g., what you observe/experience) level?
>
> *Sub-microscopic level:* How would you explain this process at the microscopic (e.g., particulate, atomic, or molecular) level?

Students were given the phenomenon tasks towards the end of class and had about ten minutes to complete the questions associated with the phenomena. The questions were administered on Qualtrics, an online survey platform. In the non-sketching group, the students were asked to reason about the phenomena without any form of sketching or conceptual modeling. In the sketching group, the students were provided with an artifact with a visual depicting the phenomenon and a few prompts that asked students about specific chemical concepts that support them in their conceptual understanding of the phenomenon, as shown in figure 3.1. The students were asked to do the sketches prior to completing the phenomenon questions; the students could then use their conceptual sketches to answer the phenomenon questions.

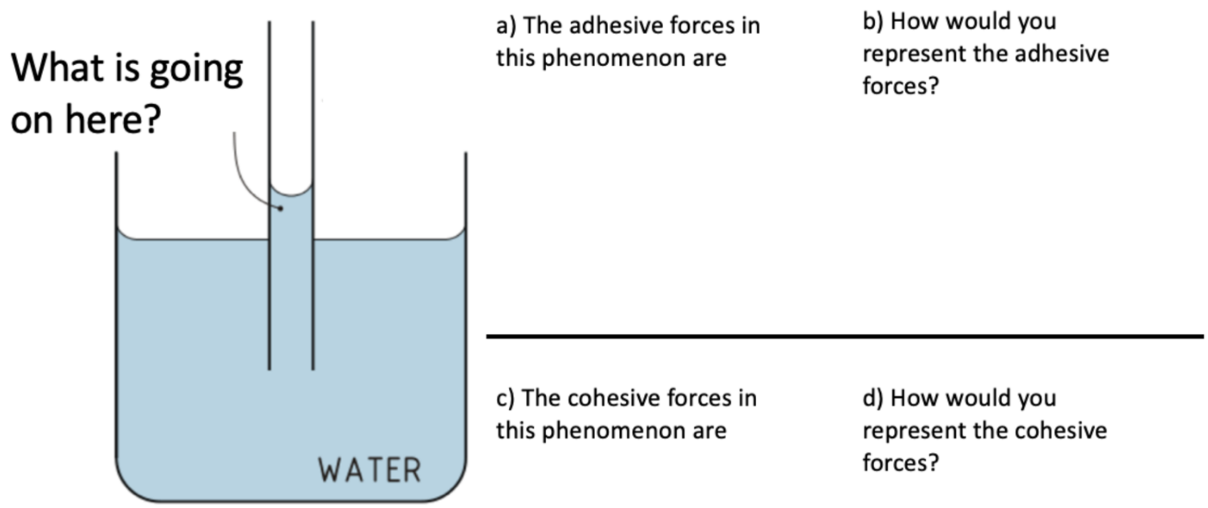


Figure 3.1 Artifact depicting the chemical phenomenon with prompts about specific chemical concepts.

Chemical Phenomenon: Macroscopic & Sub-Microscopic Levels of Representation

The data in this chapter will be analyzed for the following chemical phenomenon: why does water “climb” up the walls of an inverted test tube. Below, are the macroscopic and sub-microscopic level accounts of this phenomenon, as it will guide in the data analysis and support the reader in understanding the key attributes involved in the responses to each question.

Macroscopic level: How would you describe this process at the macroscopic (e.g., what you observe/experience) level? In the chemical phenomenon, the students observed an inverted tube being dipped into a glass of water. They observed the water rise in the tube, and then form a meniscus at the top.

Sub-microscopic level: How would you explain this process at the microscopic (e.g., particulate, atomic, or molecular) level? There are two types of particulate-level interactions in this phenomenon: the interaction between the water molecules (cohesive forces) and the water and glass molecules (adhesive forces). As the water rises in the tube, a meniscus is formed at the top. The meniscus is a result of the water molecules attraction to the glass molecules (adhesive forces) being greater than the attraction of the water molecules (cohesive forces).

3.5.3 *Data Collection*

There were two types of student work that were collected for this study: students' written accounts and students' sketches of the phenomenon.

Students' Written Accounts. In both the non-sketching and sketching groups, the students were asked to write about the macroscopic and sub-microscopic level accounts of the phenomenon described above.

Student Sketches. In the sketching group, the students were given an artifact that had prompts for the students to reflect on the phenomenon.

Data Analyses

The students' written accounts and sketches were coded for themes using deductive codes (Strauss and Corbin, 1994). Specifically, the codes were derived by using the macroscopic and sub-microscopic level accounts developed for the chemical phenomenon:

1) were students able to account for the phenomenon through the sub-microscopic interactions?

2) were students able to connect how the sub-microscopic level (e.g., particulate) connects to the macroscopic level (e.g., phenomenon)? In other words, how do the microscopic behaviors support our understanding of the observable phenomenon.

3) how do the students represent particles and particulate level interactions in their sketches?

3.6 RESULTS

3.6.1 *Research question 1: In what ways do sketches affect students' explanations of chemical events at the sub-microscopic levels?*

Finding 1: Students improve in their ability to identify the appropriate interactions between substances and particulate-level components in their causal explanation of chemical events

In the chemical phenomenon given, there are two sets of interactions present that can give a causal account of it: 1) interactions between the water molecules (cohesive forces) and 2) interactions between the water and glass molecules (adhesive forces). As shown in Table 3.1, in the non-sketching group, 47% of the students identified at least one of these interactions. Overall, 30% of the students referenced the interactions between liquids and 43% referenced the interactions between the glass and the liquid; only 28% of the students referenced both sets of interactions in their explanations. In the sketching group, 61.3% of the students identified at least one of these interactions. Overall, 34.7% of the students referenced the interactions between liquids and 57% referenced the interactions between the glass and the liquid; only 30.7% of the referenced both sets of interactions. A chi square statistic was performed over these sets of data and subsequent data to investigate whether the distribution of the categorical variables differed between the non-sketching and sketching groups. The chi square statistic yielded the following result: referencing liquid-liquid interactions, n.s., $X^2(3, N=175) = 0.43$, $p = 0.51$; referencing liquid-glass interactions, n.s., $X^2(3, N=175) = 2.90$, $p = 0.09$; referencing at least one interaction, n.s., $X^2(3, N=175) = 3.54$, $p = 0.06$; n.s., referencing both sets of interactions, $X^2(3, N=175) = 0.15$, $p = 0.70$. Thus, overall, there were no statistical differences observed between the two groups on these substance-level interactions. However, it is important to note the following qualitative trends. The students in the sketching condition were more able to identify at least one set of appropriate interactions (61.3%) amongst the substances, as compared to the non-sketching group (47%). Furthermore, 56% of the students in the sketching group were able to identify the liquid and glass interaction, as compared to 43% in the non-sketching group. This may be because the students in the sketching group were prompted to think more about the different types of interactions present in the chemical phenomenon. The prompts in the conceptual sketch (as shown in figure 3.1), asked the students to identify both the adhesive and cohesive forces in this phenomenon, thus signaling that there are two sets of interactions in this phenomenon, without implicating which substances are involved. Thus, the prompts in the conceptual sketch served as a guide to the sets of interactions that give a full causal account of the phenomenon.

It is important to note that even though the students may have identified the appropriate substances (e.g., water) that are interacting in the phenomenon, they still may not have referenced the appropriate aspect of the substance (e.g., water molecule). For example, did the students say the water was attracted to itself or that the water molecules were attracted to each other. Thus, the researchers then looked at whether the students were referencing the particulate nature of the substance in their causal explanations. In the non-sketching group, 23% of the students referenced the particulate aspects of the substance in some way, whereas, 36% of the students did so in the sketching group. This finding was not significant, $X^2(3, N=175) = 2.89$, $p =$

0.09. However, it is important to note that the sketching group had a higher percentage of students that implicated the particulate aspect of the substance. This may be because the conceptual sketches prompted students to represent the parts of the substances that are interacting. And in fact, about 64% of the students represented the particulate aspect of the substance in their conceptual sketches, as compared to their written explanations. While only 36% of the students referenced particles in their explanations in the sketching group, 64% of these students referenced particles in their conceptual sketches (as shown in Table 3.2). This was significant, $X^2(3, N=150) = 11.76, p < 0.001$.

Overall, through the process of conceptual sketching, the students were afforded the ability to make visible the particle-level components and interactions. Given that a statistically significant percent of students implicated the particle-level interactions in their conceptual sketches (64%) as compared to their causal accounts (36%), the conceptual sketch served as a medium that could better support the communication and representation of particle-level interactions. Thus, through conceptual sketching, the students were more likely to implicate the particle-level interactions that supported the sub-microscopic level of the chemical phenomenon. Thus, there are two non-mutually exclusive possibilities for this observation. One, the students may find that the conceptual sketches serve as a better medium for making visible and/or communicating particle-level interactions. Second, the two mediums may be used in a complementary nature, where there is distributed cognition amongst them, in which the particle-level interactions are better addressed through sketches, and the causal explanation of the phenomenon can be supplemented with the sketches.

Finding 2: Students improve in their ability to connect the macroscopic/observational level with the sub-microscopic/particulate level

In the chemical phenomenon given, an example of a student response where the sub-microscopic level is connected to the macroscopic level is as follows: "the interactions between the liquid and the glass are stronger than the interactions or intermolecular forces between the liquid and itself. So, the adhesive forces pull the liquid up the tube because the liquid wants to interact with the glass." In this response, the student identifies the interactions between the liquid and glass and the liquid to itself, and compares these sets of interactions to show that the liquid-glass interaction is stronger than the liquid-liquid interaction, thus leading to the liquid being pulled up the tube. Thus, the student is using the submicroscopic account to support the observed behavior. In other words, the student is connecting the sub-microscopic and macroscopic levels of the chemical phenomenon in their response. In the non-sketching group, 14% of the students were able to make the connection between the sub-microscopic and macroscopic levels, whereas, 24% of the students in the sketching group were able to do so (as shown in Table 3.1). Although this result was not significant, $X^2(3, N=175) = 2.89$, $p = 0.09$, there is still an increase in the percentage of students connecting macroscopic and sub-microscopic levels. Thus, students' ability to connect the two critical levels of representation (i.e., the macroscopic and sub-microscopic) improved in the sketching group and the students in the sketching group were less likely to describe macroscopic behaviors as sub-microscopic interactions. Thus, the conceptual sketch supported students to connect what they were observing with what was occurring at the particulate level for a chemical phenomenon. There may be multiple reasons why this may be, which are not mutually exclusive. One, the conceptual sketch had a depiction of the chemical phenomenon, which may have supported students to connect the sub-microscopic level to the observed phenomenon in their responses. Two, as the students in the sketching group were more likely to identify the appropriate interacting substances and the associated particulate level interactions (finding 1), they may be better able to connect the sub-microscopic level to their observations. It is also important to note that in the sketching group, there are still 75% of students who are not doing so. This will be further explored in the conclusion.

Table 3.1 Themes observed in students' written accounts of the chemical phenomenon in both the non-sketching and sketching groups.

Code	Example	Non-Sketching Group Students' Written Accounts (% of students)	Sketching Group Students' Written Accounts (% of students)
Describes Interactions Between Substances Involved in Phenomenon			
Liquid and Liquid Interaction (1)	"The water molecules were attracted to themselves"	30%	34.7%
Liquid and Glass Interaction (2)	"There are attractive forces between the solution and the	43%	56%
One Set of Interactions are Described (1) or (2)		47%	61.3%
Both Sets of Interactions are Described (1) & (2)	"The liquid was more attracted to the glass than its own molecules"	28%	30.7%
Ambiguous	"There is a lower IMF" (intermolecular forces)	26%	22.7%
None	"You would need to see at a microscopic level"	27%	17.3%
Mentions Particulate Components of Substances	"The water molecules were attracted to themselves created a concave in the tube"	23%	34.7%
Connects the Macroscopic Level to the Sub-Microscopic Level	"The interactions between the liquid and the glass are stronger than the interactions or Intermolecular forces between the liquid and itself. So the adhesive forces pull the liquid up the tube because the liquid wants to interact with the glass"	14%	24%
Only Discusses Macroscopic/Observational Behaviors	"The water molecules were forced up the tube"	10%	2.6%
I Don't Know/Not Sure/No Responses	"Not sure"	6%	4%

Table 3.2 Themes observed in students' written accounts of the chemical phenomenon in both the non-sketching and sketching groups, as well as the students' sketches in the latter group.

Code	Written Account of Non-Sketching Group (% of Students)	Written Account of Sketching Group (% of Students)	Sketches (% of Students)
Describes Interactions Between Substances Involved in Phenomenon			
Liquid and Liquid Interaction (1)	30%	34.7%	52%
Liquid and Glass Interaction (2)	43%	56%	64%
One Set of Interactions are Described (1) or (2)	47%	61.3%	64%
Both Sets of Interactions are Described (1) & (2)	28%	30.7%	52%
Ambiguous	26%	22%	11%
None	27%	17%	3%
Mentions Particulate Components of Substances	23%	36%	64%

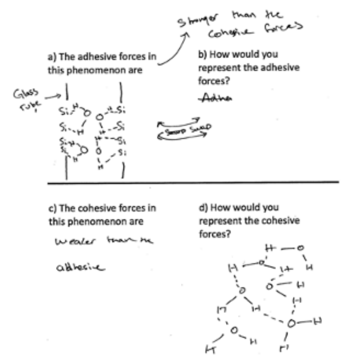
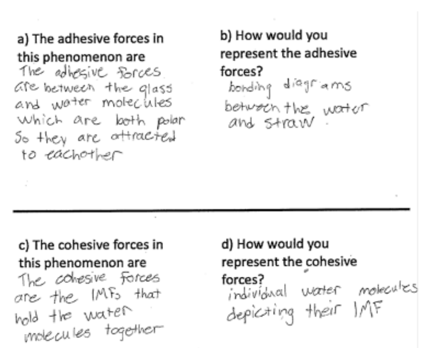
3.6.2 *Research question 2: How do students represent the interactions in a chemical phenomenon is their sketches as compared to their causal explanations?*

Finding 3: Students' ability to represent substance and particulate interactions improves in their conceptual sketches as compared to their causal explanations

As noted in finding 1, 64% of the students in the sketching group represented the particulate aspect of the substance in their conceptual sketches. Whereas, only 36% of the students referenced particles in their explanations. This is true of students who represented the particulate aspect of the substances using both molecular structures and textual representations. In fact, 80% of the students represented the substances using text and only 9.3% represented them using molecular structures (as shown in Table 3.3). Thus, even though the students were not able to draw the particulate structures of the substances, they were still able to implicate the involvement of the appropriate particles in their interactions (e.g., water molecules). This is a very important to note because even though students may not be able to know or visually represent the chemical structures involved in a phenomenon, they are still able to identify the interactions are occurring between the particulate aspects of substances.

Furthermore, as shown in Table 3.3, for the students in the sketching group, 30.7% of the students described both sets of interactions in their written explanatory accounts and 52% did so in their conceptual sketches; this result was significant, ($X^2(3, N{=}150) = 7.04$, $p < 0.008$). Thus, through their conceptual sketches, the students were more likely to make visible the interactions between both sets of substances. This is critical, as to have a full causal account of the phenomenon requires one to reason between both the liquid-liquid and liquid-glass interactions. It is also important to note that the percentage of students that provided ambiguous or no responses about the substance interactions was lower in the conceptual sketches as compared to the written accounts. There was ambiguity in 22% of the written accounts and 9% of the conceptual sketches, and no response was given for 17% of the written accounts and 2% of the conceptual sketches. Thus, for many, the conceptual sketch served as a better medium to express the substance interactions, however, it is important to note that the sketches and the written accounts should be viewed holistically and not in isolation. The National Research Council's report (2014) on *Developing Assessment for the Next Generation Science Standards* points out that assessment tasks "should have multiple and convergent forms of evidence for use in holding schools accountable for meeting learning goals (p. 208)". In the current context, conceptual models complement the written explanations and vice versa. Even though the conceptual sketches were more likely to make visible the interactions between substances and the particulate level interactions, the sketches were not done in isolation. In a survey conducted at the end of the course, students were asked in what ways sketching supported them. One student said, "sketching helped when using words to describe something did not" and another student said that "drawing helps you picture out what you are explaining." Thus, conceptual sketching and written accounts are complementary in nature, where a sketch can provide the basis for representing chemical concepts which may difficult or inaccessible through words. Furthermore, they provide a physical and stable representation that can be more easily manipulated and visualized.

Table 3.3 Students' representation of the substances implicated by format, percentage, and examples.

Format of Representation	Percentage of Responses	Example
Molecular Structure	9.3%	
Text	80%	

3.7 Conclusions and Implications

The current study investigated: 1) in what ways do sketches affect students' explanations of chemical events at the sub-microscopic levels, and 2) how do students represent the interactions in a chemical phenomenon in their sketches as compared to their causal explanations? For the first question, the study found that more students who engaged in conceptual sketching were better able to identify the interactions between the appropriate substances in the chemical phenomenon in their explanations, as compared to the students in the non-sketching group.

Furthermore, a greater number of students in the sketching group were better able to implicate the particulate nature of the substances in making sense of the interactions, as compared to the non-sketching group. The characteristics of the conceptual sketch supported students in these actions, as the sketch prompted students to identify and represent the appropriate sets of interactions, which led to their explanations referencing appropriate interactions, both between the substances and the sub-microscopic level.

Furthermore, a greater number students in the sketching group (as compared to the non-sketching group) were more likely to connect the sub-microscopic interactions to the macroscopic or observational level. This may have occurred for two reasons, which are not mutually exclusive. First, the sketch may have supported students in visualizing how the substance and sub-microscopic interactions supported the observational account. Second, the conceptual sketch contained a depiction of the phenomenon, thus serving as aid for the students to connect the macroscopic and sub-microscopic levels of representation. Thus, the properties of the sketch made visible both levels of the phenomenon simultaneously and connectively.

For the second question, the study found that more students were able to represent the interactions between both the appropriate substances and the particulate aspects of the in the chemical phenomenon in the conceptual sketch as compared to their written explanation. The prompts in the conceptual sketch (as shown in figure 3.1), asked the students to identify and represent the adhesive and cohesive forces in this phenomenon. This prompt not only signals to the students that there are two sets of interactions involved in this phenomenon, but it also encourages them to think about how the interactions are occurring. This may be why it was observed that the students were more likely to represent the particulate-aspects of the interactions in the conceptual sketches as compared to the written explanations. Thus, the sketches may serve as a better medium to communicate and/or make visible both substance interactions. However, it is very important to note that the sketches are not an isolated activity, rather they are paired with a causal explanation. The concepts that can be made visible through a sketch may be very different from that of an explanation. Thus, the two acts (sketching and writing an explanation) are complementary and should be coordinated during interpretation; where a sketch can provide the basis for representing chemical concepts which may difficult or inaccessible through words and the explanation can provide the links between the causal and observed accounts (Windschitl, Thompson, and Braaten, 2008). Thus, the conceptual sketching not only served as source of sense-making (left triangle in figure 3.2), but it also served as a source of the development of representational competence, the students' ability to link the macroscopic and sub-microscopic accounts of a phenomenon (right triangle in figure 3.2).

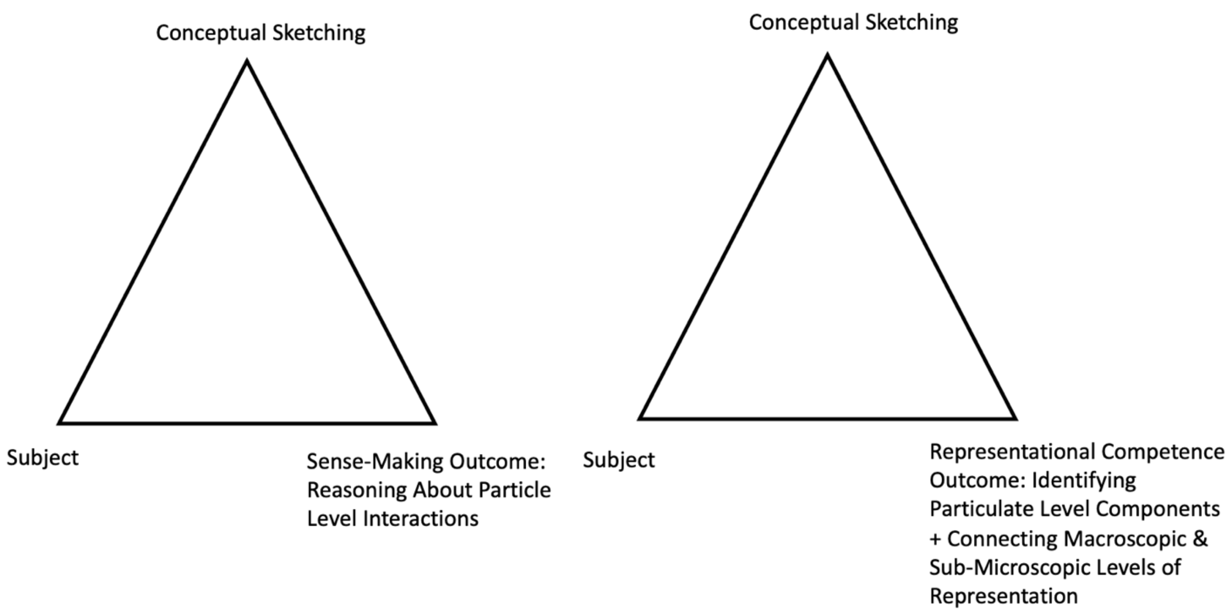


Figure 3.2 Schematic demonstrating how a conceptual sketch serves as a mediating object to support both sense-making (reasoning about particle level interactions) and representational competence (identifying particulate level components and connecting macroscopic & sub-microscopic levels of representation).

To assess representational competence, the students' abilities to connect the macroscopic observation to the sub-microscopic interactions was analyzed. While 14% of the students in the non-sketching group were able to connect the two levels, 24% were able to do so in the sketching group. Even though there is a 10% increase in the sketching group, 76% of the students were unable to connect the macroscopic and sub-microscopic levels. In the task, the students were asked to describe the macroscopic observation and then to explain it from a sub-microscopic account. Thus, students may have found it redundant to mention the observation again in the second account and/or they may not have known how to connect the two levels (e.g., the students can describe the sub-microscopic interactions, but do not how to connect this account to the observation). Given that this is an important aspect to representational understanding in chemistry (Johnstone, 1993; Stieff, 2011), future implementations of the task can provide students with examples that show how connecting the representational levels can give a fill account of the phenomenon. Thus, the examples can model the task in a manner that makes the epistemic goals of the activity visible (Lehrer, 2009).

The present study was conducted in an undergraduate chemistry course with over 100 students. The students engaged in written accounts and conceptual sketches over the course of the quarter; about ten minutes of class time was allocated for the task. The instructor emphasized that the sketches would not be graded and served as an opportunity to make sense of a chemical phenomenon. Thus, this task did not take a lot of time, and it was framed as being low stakes. This is a practice that can be embedded in large enrollment STEM undergraduate courses.

Based on the findings, the following considerations can help move the conversation move forward on designing effective learning environments for students to engage with the macroscopic and sub-microscopic levels of representation in chemical phenomena. First, it is important for students to be able to represent the particulate-level interactions occurring in a phenomenon. The understanding of a phenomenon from a sub-microscopic is difficult, because it cannot be immediately experienced or visualized. The chemistry education research has shown that students systematically attribute macroscopic level features to sub-microscopic phenomenon (Harrison and Treagust, 1996), and thus have difficulty in appealing to the particulate-level when explaining an observed chemical phenomenon. Given that this is the learner's starting point in instruction, this should be taken into consideration when designing lessons. Students, by themselves, cannot deduce what the sub-microscopic level looks like on their own, and thus need appropriate tools to "discover" what the sub-microscopic world looks like would not be appropriate.

For example, Ardac and Akaygun (2004) and Russell, et al. (1997) used different multimedia presentations that would simultaneously show the chemical equation for the reactants and products (i.e., symbolic level), and what the reactants and products looked like at the macroscopic and microscopic representational levels. Both studies showed an increase in conceptual knowledge in the chemical content areas that were introduced in the multimedia presentations at the secondary and post-secondary levels, respectively. Thus, linking these three key representations can help students understand a phenomenon at all three levels of chemical representation. This can lead to the development of representational skills or competencies that allow students to move flexibly across the three levels of representation for any given chemical phenomenon (Kozma, et al., 2000). In the end of the quarter survey, a student reflected that through sketching, "it helped to visualize what was going on." Thus, external representations (e.g., conceptual sketching) can support students in visualizing the phenomenon and making explicit the connecting between the different levels of chemical representation that are implicated (right triangle in figure 3.2).

Second, students should have multiple opportunities to construct and reflect on their conceptual understandings, and they should do so both in explanatory and sketching formats. In the context of conceptual modeling, activities like sketching (Cooper, Stieff, and DeSutter, 2017) and development of models (both public and private) should be done in tandem to support the understanding of a phenomenon (Windschitl, et al., 2012). These activities, when done in coordination, can help students understand the key features of a phenomenon and how they are related (Windschitl, Thompson, Braaten, 2008),

Furthermore, these coordinated activities provide not just instructors but also students to opportunity to monitor their own understandings, or identify gaps in their thinking (Windschitl, Thompson, Braaten, 2008). In the end of the quarter survey, students reflected that through the act of sketching, “I had a chance to define my strengths and weaknesses in understanding the topic” and “it really made sure I actually understood what was going on.” Thus, through sketching, students became engaged in the self-monitoring of their ideas. There is research that demonstrates that self-monitoring can support conceptual understanding. For example, during a scientific inquiry cycle, White and Frederickson (1998) asked students to reflect on their conceptual understandings and their engagement in the inquiry process. First, they found that students who were better able to justify their self-assessment score with the appropriate evidence had higher quality projects. Thus, students who were internally engaging in self-reflection had greater awareness of where they were conceptually, which in turn, could have led them to engage in further learning to close conceptual gaps. In this study, the students were not explicitly asked to engage in self-monitoring of their ideas, but the act of self-monitoring emerged through the act of self-sketching, where students became aware of what they did and did not know (left triangle in figure 3.2).

Third, sometimes in chemistry, material supports are faded out because they are viewed as a scaffold, and thus, students no longer have access to them during critical times of sense-making, like on summative assessments. This may be theoretically and practically unsound. For example, Pea (2004) gives the example of how the act of computing would be unachievable without the computer. Thus, the device has become a part of the activity, where subject and the tools together constitute a form of distributed intelligence. Similar, to the role that the conceptual sketch played in this study.

The visualization tools (whether on paper or computer) enable the acts of distributed intelligence whereby students can make sense of the unobservable, and in fact, this is a practice, which is observed in practicing chemists. Scientists do not rely simply on mental models; their practice is dependent upon external visualizations, which include diagrams and simulations (Kozma, 2000). To leave these external visualizations out of the reasoning process can inhibit meaning making and not enable students to become fluent with the different material means that chemists use to make sense of the chemical phenomena with which they are engaging. In the end of the quarter survey, students reflected that sketching supported them "to have a visual representation of what was happening and would be easier to explain" and "rather than thinking about it, being able to visualize it helped a lot." Thus, through sketching, students were assisted in the visualization of the phenomenon, which supported them in their sense-making of it (left triangle in figure 3.2). Thus, to become chemists, one must be able to act in the context of availability of the appropriate tools to achieve the desired end goals (Pea, 2004). These tools are not just the tools of the trade, but include tools (e.g., conceptual sketches) that support in sense-making. This is not just true of practicing chemists, but emerging chemists as well.

Chapter 4. SUPPORTING SCIENCE TEACHERS IN SENSE MAKING AROUND STUDENTS' FACETS OF THINKING AND THE STUDENT EXPERIENCE IN SCIENCE CLASS

The complex profession of teaching science requires years of coordinated learning and expertise development. Berliner (2004) talks about the characteristics that expert teachers bring to the work of teaching. In one study (Berliner, et al., 1988), the researchers noted that expert teachers not only understand their students' cognitive abilities, but also have a history with their students, which helps to shape their interactions with them. These two components are an important aspect of teaching, and teaching in science, as they enable teachers to draw on students' knowledge, interests, and experiences to shape learning experiences. Thus, models for teacher learning should support teachers to draw on these components in the design of meaningful learning experiences for their students.

The Framework for K-12 Science Education (NRC, 2012) talks about the new vision for science education, which involves a coordinated effort by all parts of the science education systems. The Framework calls out the importance of teacher preparation and professional development for widespread implementation of the enactment of the vision that can support equitable and rigorous science learning. In the Framework's recommendations for in-service science teachers, also known as practicing science teachers in the research literature, it states that "professional development should not only be rich in scientific and engineering practices, crosscutting concepts, and disciplinary core ideas but also be closely linked to teachers' classroom practices and needs (p. 259).” Furthermore, it notes that “ultimately, the interactions between teachers and students in individual classrooms are the determining factor in whether students learn science successfully (p. 255).” These interactions include an attention to both rigorous and equitable models for learning in science. The Framework identifies multiple levers to promote equity, including building on students’ interests and identities and cultural funds of knowledge. These recommendations require multiple dimensions of teaching and learning to be coordinated together during professional development sessions. What are science teachers’ current pedagogical practices and professional learning needs? How do teachers leverage and draw on students’ conceptual and cultural resources in sense-making? How do they leverage and mobilize instruction around students’ interests and identities in the science classroom? This chapter will be exploring possibilities for professional learning for practicing science teachers around these important questions.

This chapter will first talk about different models of learning for practicing science teachers. Specifically, drawing attention to important characteristics for the models of learning that are implicated in this study. Second, it will talk about the role that practical measures – data gathering methods that quickly sense activity and perspectives of participants - can play in the unfolding design of learning opportunities for practicing science teachers. To do so, it will talk about how practical measures as an implementation sensing infrastructure fits in with the design-based implementation research (DBIR) approach to and the role that research + practice partnerships can play in the effort to support systemic change. It will then theorize about how practical measures can facilitate learning by serving as boundary spaces across multiple sociocultural places and drawing on the models of learning for practicing science teachers. Finally, the chapter will situate the importance of attending to two less studied dimensions of science teaching and learning: students' facets of knowledge (Minstrell, 1989) and students' lived experiences in the science classroom.

4.1 MODELS OF LEARNING FOR PRACTICING SCIENCE TEACHERS

Luft and Hewson (2014) provide a review on professional development programs (PDPs) and the important characteristics of PDPs in science. They highlight that for those who engages in PDPs, the focus is on professional learning, which is viewed as on-going, personal and professional, and individual and collective. Thus, the learning involves dynamic, complex, and iterative interactions (Opfer and Pedder, 2011) of teachers, schools, learning activities, and can include teams of researchers and practitioners.

Luft and Hewson (2014) conducted a comprehensive review of the research literature of science teacher PDPs in the United States. It is important to note that in their initial search they identified around 200 research articles, but narrowed it down to around 50, to exclude articles that talked about the same program or did not have information given about the program. The parameters for inclusion in the review included two aspects: 1) the study was described or was situated in a science teacher PDP and 2) the study was focused on practicing science teachers. In their synthesis, they identify four key features:

1. Teachers experience different degrees of change in the midst of PDPs
2. Collaboration is important in supporting teacher growth
3. Coherency is important in science teacher PDPs
4. Content knowledge is an important component of a PDP

Effective science teacher PDPs involves all or a subset of these features. While all of these features should be taken into account when designing PDPs, the present study will specifically expand on and explore how features two and three were supported in a set of PD sessions for science teachers: collaboration and coherency.

Feature 2: Collaboration is important in supporting teacher growth. Prior research has looked at how Professional Learning Communities (PLCs) support teacher growth (Richmond and Manokore, 2011). In their analyses of teacher dialog during PLC meetings, they found that PLCs played an important role in developing teachers' confidence in content knowledge and practice, and promoting a collaborative community which encouraged science teachers to examine their own learning and to support the learning of others (Richmond and Manakore, 2011). They go on to argue that community is a key aspect in improving teacher practices and student achievement, and that the most effective PLCs should involve teachers both within and outside buildings. Although, this argument was made with respect to PLCs, it can be extended to professional development sessions outside of the building, where teachers from multiple buildings come together to reflect on their shared and diverging experiences in science teaching, curricula, instructional strategies, and students' thinking and experiences. As Putnam and Borko (2000) note, these discourse communities provide individuals the tools to make sense of their experiences, where learning is enculturation into a community's way of thinking (Lave and Wenger, 1991). Thus, professional development sessions should involve opportunities for practicing teachers from multiple buildings to collaborate on these shared endeavors to yield novel and innovative ways of teaching and learning science.

Feature 3: Coherency across contexts is important in science teacher PDPs. McDonald, Kazemi, and Kavanaugh (2013) emphasize the importance of coherency across different settings for teacher education: controlled (e.g., methods course at a university), designed (e.g., methods course in a K-12 school), and authentic (e.g., school and/or classroom). Kazemi and Hubbard

(2008) emphasize the importance of coherency between PD and classroom settings, where learning is not unidirectional (e.g., PD to classroom); rather the PD and classroom settings coevolve with the participants' goals and needs. The models put forth for both pre-service and in-service teacher learning, respectively, take a situative approach to learning, which views learning as a collective activity that is mediated by conceptual and material tools (Wenger, 1998; Cole, 1996).

McDonald, Kazemi, and Kavanaugh (2013) note that a common framework across the learning cycle can allow the exchange of ideas across the settings. They highlight the importance of connecting authentic and ambitious activity across different settings, especially "because the field has no common language with which to make scholarship and practice relevant across settings, it is rare for knowledge produced in one setting to influence work in other settings." Thus, a critical aspect in the design of professional development experiences for practicing science teachers needs to connect authentic activity across different settings.

4.2 Leveraging practical measures for the design of PD for practicing science teachers

Luft and Hewson (2014) call out that local contextual elements (e.g., language needs of students) should be considered in the design of PDPs and that the collection of data is essential to revise the program, leading to an adaptive PD that is responsive to the teachers' needs. Thus, the need to for data that is sensitive to the local context and that can result in activities that are responsive to the needs of the teacher can lead to PD that has coherency across settings.

One mechanism to gather data that is sensitive to the local context and responsive to the work of different settings involves the use of practical measures. Practical measures are borne out of improvement research, which draws on a "natural human bent to learn by doing" (p. 7, Yeager, et al., 2013), and thus it seeks to “integrate research evidence into practice” (p. 7, Yeager, et al., 2013). Thus, practical measures differ from traditional forms of measurement, which tend to focus on systems of accountability and theory-building (Yeager, et al., 2013).

Practical measures must leverage data that is “collected, analyzed, and used within the daily work lives of practitioners” (Russell and Grunow, 2015). In this statement, there are multiple concepts embedded about the nature of practical measures. First, practical measures must be a way to sense on-the ground implementation. Thus, the measures must be situated in the everyday work of practitioners. These measures use language that is relevant and meaningful to practitioners, and the data collection should be embedded in the routines of practitioners (Jackson, et al., 2016; Yeager, et al., 2013).

Second, there need to be iterative cycles of inquiry to improve educational improvement efforts (Jackson, et al., 2016; Yeager, et al., 2013). The driving force behind the use of practical measures is to bring research evidence into practice, thus there must be multiple points of analysis, reflection, and design around the practical measures data. Through this process, one can identify levers of improvement to bring about systemic change. It is important to note that practical measures can be characterized of having properties, such as having validity and reliability. The practical measures in this study take an ecological approach that centers the participants’ experiences and perspectives so that it can: 1) “provide voice to educators to describe inequitable situations and phenomena”, and 2) “provide ongoing situated information about learning phenomena that can be used to guide equity focused improvement efforts in the partnership” (Bell, et al., in preparation). Thus, the use of practical measures in this study is to shine a light on systemic inequities, elevate the multiple voices and interpretations, and to make visible the dimensions of science teaching and learning that include and go beyond content and practice.

Leveraging practical measures requires that there must be a sociotechnical infrastructure in place that allows for the data to be analyzed, interpreted, and used to guide the design of professional learning opportunities as they unfold. Research and practice partnerships can provide one type of intellectual and material infrastructure necessary to make sense of and design around this data (Coburn & Penuel, 2016). Research-practice partnerships are "long-term, mutualistic collaborations between practitioners and researchers that are intentionally organized to investigate problems of practice and solutions for improving district outcomes" (Coburn, Penuel, & Geil, 2013, p. 2). RPPs can leverage the data from practical measures which can help provide research around and design solutions towards improving science education. Cobb, et al., (p. 9, 2003) describe DBR as involving "design-experiments entail both 'engineering' particular forms of learning and systematically studying those forms of learning and systematically studying those forms of learning within the context defined by the means of supporting them." Thus, DBR, by nature is interventionist and affords the opportunity to develop both design knowledge and theoretical knowledge about learning and cognition (Cobb, et al., 2003; Linn, Davis, and Bell, 2004; Bell, 2004; Fishman, 2014). Design-based implementation research (DBIR) builds on the same principles and also focuses on persistent problems of practice from the perspective of multiple stakeholders, a commitment to iterative and collaborative design, and the capacity to develop change in systems that is sustainable (Fishman, 2014; Penuel, Fishman, Cheng, and Sabelli, 2011). In RPPs, the goals and aims of the work are collaboratively supported by researchers and practitioners. Through the use of practical measures, the partnership can sense the emerging problems of practice and opportunities for improvement.

One of the challenges in education is to create possibilities and conversations across boundaries, where a boundary is a "sociocultural difference learning to discontinuity in action or interaction" (P. 133, Akkerman and Bakker, 2011). These boundaries are present in different settings in teacher education, as they each have their own cultural norms and practices (McDonald, Kazemi, and Kavanaugh, 2013). The boundary can be seen in the middle of two interacting activity systems (Akkerman and Bakker, 2011; Engeström, et al., 1995). An important question is *how does one navigate this boundary*? One can view boundaries as problematic or as an opportunity to establish communication and interaction (Akkerman and Bakker, 2011). When viewing it from the latter perspective, this can support dialogical learning which strives to capture multiple and nuanced meanings (Akkerman and Bakker, 2011; Bakhtin, 1986).

There are multiple dialogical learning mechanisms implicated when engaging in boundary crossing. One learning mechanism that will be expanded on in this study is the mechanism of reflection. Reflection involves "realizing and explicating the differences in practice" (p. 144, Akkerman and Bakker, 2011). There are two characteristics of reflection: perspective-making and perspective-taking (Akkerman and Bakker, 2011). In perspective-making, one is making explicit their understanding of an issue (Boland and Tenkasi, 1995). Thus, one is making explicit one's understanding by "reflexively giving access to the implicit and unstated assumptions" (p. 364, Boland and Tenkasi, 1995) by making explicit the knowledge mobilized in interpreting the object (Hoyles, at al., 2007). In perspective-taking, one is "taking of the other into account, in light of a reflexive knowledge of one's own perspective, is the perspective-taking process" (p. 362, Boland and Tenkasi, 1995). Taking another perspective can enable one to have a richer, nuanced understandings. In the present study, these dialogical learning mechanisms will be explored as researchers and practitioners make sense of practical measures data from teachers and students; this will occur in two cases. In the first case, the data from the teacher practical measures will shed light on how teachers are thinking about the challenges that high school chemistry students are experiencing in the classroom. In the second case, the data from the student practical measures data will shed light on middle school students' experiences in the science classroom.

The practical measures can serve as a boundary object in that it fulfils a bridging function across socio-culturally distinct spaces, which include (Star, 1989; Akkerman and Bakker, 2011): the science classroom as an instructional context, the professional development space as a professional learning context, the PD co-design space with the research-practice partnership engaging in design decisions, whereby the practical measures can engage and includes multiple and diverse experiences across these boundaries. Thus, the use of practical measures data, operating through the PD co-design space, (as it will be shown in the two cases), can be aligned with the critical features of PDPs: connecting teachers experiences in the classroom and PD settings (coherence) and providing a shared sense-making around data from classroom enactment (collaboration).

4.3 Two key aspects of design: Identifying students' facets of knowledge and students' experiences in the science classroom

A facets approach to student thinking does not view students' ideas as right or wrong; rather, it views them as "stepping stones to understanding" and teachers can engage with them in deeper ways to support learning (Bell & Minstrell, 2016; Minstrell, 1989). Minstrell (1989) emphasized the importance of viewing these ideas as operational ways of reasoning that students bring to science. Thus, students are viewed as having linguistic, experiential, and conceptual resources that they can use to advance their scientific understanding (Warren, et. al, 2001). And the approach to students' facets acknowledges that that students bring heterogeneous ways of reasoning and thinking in science and the goal of science education is about knowledge refinement and reorganization, rather than replacement (Smith III, et al., 1994). Where refinement includes adding new ideas, making connections amongst ideas at multiple levels, and developing more nuanced criteria for evaluating ideas (Linn, et al., 2006). This perspective also conceptually aligns with the view that the heterogeneity of human cultural practices is fundamental to learning (Rosebery, et al., 2010; Bang, Medin, and Atran, 2007), where students are holders of diverse repertoires of knowledge that include their everyday experiences and cultural epistemologies that can be used to advance scientific understanding (Warren, et al., 2001).

The research on students' experiences in the science classroom includes multiple dimensions. The goal of this study is not to characterize all of these dimensions. Rather, it is meant to identify a few of these dimensions, especially those that relate and can be coordinated to the overarching goals of the design of the teacher professional development, which will be formally described in the methods section. Specifically, the present study will focus on the following dimensions of the student experience: students' interests in science class and students' reflection on learning with science talk activities. These will be collectively referred to as the student experiences for this study.

Students interests in science class. Student interest is foundational for meaningful learning in science (NRC, 2009; NRC, 2012). Lyons (2006) interviewed students to understand their experiences in the science classroom. Lyons found that some students perceived the course content to be irrelevant to their interests and aspirations, and that they appreciated it when their teachers tried to connect every-day life contexts in their instruction. This has been shown in other studies, where students learning can be constrained when classroom science activities do not leverage students' identities and experiences (Bricker and Bell, 2014). Thus, a cultural learning pathway approach to science instruction facilitates students' connections of scientific ideas and phenomena through time, space, and social practice, to allow meaningful and consequential learning (Bell, at al., 2012).

Students' reflection on learning with science talk activities. Ohlsson (1995) describes discourse as a medium that can stimulate reflection and enhance conceptual understanding. Discourse can occur in a variety of forms, from all-class science talk to small group discussions which can take on a variety of formats (Wingert, 2016; Kasten, 1997). And discourse should support both rigorous academic learning and promote equity (Michaels, O'Connor, and Resnick, 2008). In the present study, students will be asked about their experiences around science talk in the classroom, from an equitable participation perspective, asking them questions ranging from whether they were able to talk in class, to the dimensions of talk activities that help/do not help them learn.

4.4 Present study and research questions

The data for this study comes from a three-year partnership between two school districts, the university, and a non-profit science research organization. The partnership set forth numerous goals in their work including: supporting the implementation of for three-dimensional science teaching (NRC, 2012), promoting inclusive discourse strategies, developing and integrating three-dimensional formative assessments, promoting culturally relevant teaching, and attending to students' interests and experiences in the science classroom.

The surveys in the practical measures were set-up to reflect the goals of the partnership, so that they could understand the teachers' and students' experiences with respect to the goals of the partnership. Some of the questions on the teachers' and students' practical measures asked about similar constructs with the intent of triangulation across teachers' and students' experiences. The data were analyzed during meetings between the researchers and practitioners to understand the needs of the teachers and how this could be used to inform the design of science teachers' professional learning. The researchers are learning scientists focused on science education working closely with district science staff and PD providers from a non-profit science research organization. The study will illustrate the data being used in two different cases. Specifically, it will highlight how the data was used in the design of professional learning sessions that supported teachers to attend to students' facets of thinking (case 1) and students' experiences in the science classroom (case 2); two critical areas that should be attending to in teaching and learning.

In the first case, the data from the teacher practical measures was used to design professional learning sessions for high school chemistry teachers around the facets of student thinking in chemistry. It will look at how the research and practice made sense of the data from the practical measures and how it was used to inform the design of the professional learning experiences for chemistry teachers. Specifically, this case shows: ***how can practical measures be used to guide the design of a series of professional learning experiences unfolding with high school chemistry teachers?***

In the second case, the data was leveraged in the design of a professional learning experience for middle school science teachers around attending to the student experience in science classrooms. This data was drawn from the five teachers who initially administered the student practical measures to their students. A professional development session was designed with this data to show teachers the possibilities in the ways that students can express their interest or lack thereof in science, and their knowledge about how all class science talk does or does not work for them. It will look at the teachers' takeaways from the session, and their subsequent behaviors around administering practical measures and their sense-making around this data. Specifically, this case shows: ***in what ways can professional development support teacher sense-making and learning by collecting data around students' experiences in the science classroom?***

4.5 METHODS

4.5.1 *Research Design and Participants*

This a design-based implementation research study which unfolded over the course of three years; it involves a university, two school districts, and a non-profit science research organization. This collective group will be referred to as the Science and Engineering Practices Collaborative (SEPC) from here on out. The SEPC came together to co-design professional development sessions for science teachers that involved approximately 80 middle school science teachers from the Creston School District and 23 high school science teachers from the Brentwood school district. The CSD has an enrollment of over 53,000 students, with approximately 11,000 middle school students. For the middle school population, the demographic breakdown is as follows: 47% White, 15% Black or African American, 14% Asian, 12% Hispanic, 11% as multiracial, 1% Native American or Pacific Islander. Approximately 10% of the middle school student population was identified as being English-Language Learners and 35% qualified for free or reduced lunch. The BSD has an enrollment of just over 16,000 students, with over 4,000 high school students. For the overall population, the demographic breakdown is as follows: 25.3 % Hispanic, 24.9% Asian, 24.6% White, 14.3% Black or African American, 9.4% as multiracial, 1.1% Native American or Pacific Islander. Approximately 17.7% of the student population was identified as being English-Language Learners and 50.3% qualified for free or reduced lunch.

4.5.2 *Design of Professional Development Sessions*

The scope of the initiative included multiple objectives. The SEPC, over the course of this three-year phase of the partnership, (following an overlapping prior three-year phase), engaged in the following overarching goals with science teachers: designing 3-dimensional instruction (with a focus on the practices of modeling, argumentation, and explanation), implementing equitable discourse strategies, designing and making sense of student work around 3-dimensional formative assessments, incorporating phenomena in instructional units, and attending to and designing around the students' experiences in science class. The general structure of the partnership involved a five-day summer institute and 3-4 release days throughout the school year. During the summer institute, teams of teachers developed and adapted instructional units that they would implement during the school. During the release days throughout the school year, the teachers continued to refine their adapted units from the summer, jointly made sense of student work, designed 3-dimensional assessments, and incorporated student discourse strategies into their work. To support teachers in their work, the partnership leveraged a variety of professional learning resources and tools, including STEM Teaching

Tools, Talk Science Primer, Ambitious Science Teaching, ASU Modeling Instruction, and Observing for Evidence for Learning cycles.

4.5.3 *Design of Teacher Practical Measures*

During the professional development days throughout the school year, the teachers engaged in a variety of professional practices including adapting adopted curricula to the new standards, collaboratively analyzing and learning from student assessment responses, developing formative assessments, and re-designing instruction to embed talk strategies into sense-making. A critical part of the professional development was being able to design activities that were responsive and appropriate to teacher needs as the effort unfolded. To do so, the partnership developed a set of practical measures to support their work. Table 4.1 shows sample questions (please see Appendix C for a full list of questions). The practical measures consisted of weekly survey questions for teachers which were designed with the following objectives: create survey items that are relevant and meaningful to the work of practitioners, enable the team to sense implementation around the project's goals and understand what is happening "on the ground", and interpret this data to inform the design of future professional learning. The items in the practical measures were refined over time to encompass the evolving interests of the partnership, incorporate teacher feedback around items, and to "nudge" specific behaviors in teachers (Bell, et al., in preparation). The data from the practical measures were analyzed and made sense by the SPEC to inform the design of the professional learning experiences for teachers. It is important to note that the practical measures were not the only factor that influenced the design of the PD sessions, and they were leveraged in the design of some sessions more than others.

The teachers were given three sets of surveys that assessed the different constructs and were rotated across 24 weeks. The first survey focused on equitable 3-dimensional instruction, the second survey focused on equitable discourse strategies, and the third survey focused on formative assessments, phenomena, and student interest. The survey, on average, consisted of 10

Table 4.1 A subset of the constructs and questions from the teacher and student practical measure surveys.

Construct	Teacher Practical Measures Questions	Student Practical Measures Questions
Three-dimensional Teaching and Learning	Briefly describe how you integrated these Disciplinary Core Ideas (DCI), Science and Engineering Practices (SEP), and Crosscutting Concepts (CCC) in your instruction this week.	What specific activities did you do in science class today? I worked on the following practices in my science class today... (please check up to **two** practices that you worked on today)
Science Discourse	Describe what your students did during all class science talk. What went well with discourse strategies? What challenges did you encounter with discourse strategies?	I learn a lot better when we talk in whole class discussions Not at all A little bit A fair amount A lot (If Not at all/A little bit selected) What is not helpful to you during whole class discussions? (If A fair amount/A lot selected) In what ways does whole class discussion help you learn?
Engaging Students with Phenomenon	In the past week, what phenomenon did your students make sense of? How did you incorporate students' experiences and/or interests in the phenomenon?	The work we did in science class was interesting to me Not at all A little bit A fair amount A lot (If Not at all/A little bit selected) Why were the activities in science class not that interesting to you? (If A fair amount/A lot selected) How were the activities in science class interesting to you?

questions, and took the teachers 7-15 minutes to complete. The teachers were given $5 for every completed survey. For case 1, the study will show how the SEPC team interpreted the practical measures data from the chemistry teachers and how this interpretation was used to inform the design of PD. The data that the SEPC interpreted involved the survey data from 6 chemistry teachers, and the total number of teachers participating in the PD was 9.

4.5.4 *Design of Student Practical Measures*

The SEPC wanted to help expand teachers' views of formative assessment as not just attending to students' science content knowledge but also to their experiences in the science class. Thus, the SEPC developed a set of practical measures for students that were aimed at understanding the student experience in science class, where table 4.1 shows some of the sample items (please see Appendix D for a full list of the questions). For over five years, the research team had previously used exit ticket styled practical measures with students across multiple projects; those efforts informed the approach to items in SEPC. The items were iterated on multiple times so that they used appropriate student language and response options, captured teacher feedback, and were flexible to be used across all content areas that served both BSD and CSD, thus high school and middle students, respectively. Two short surveys were developed that focused on two aspects of the student experience in the science class: students' self-reported experiences of how they did/didn't find science class interesting and how aspects of learning related to all class science talk. For shorthand purposes, the first survey was called the Interest Survey and the second survey was called the Science Talk Survey. The surveys also asked students (anonymously) to self-identify using demographic categories (students of color, speaks one or more languages at home other than English, and gender) so that the teachers could understand the experiences of different groups of students. The teachers were given the link for the surveys, and the data from the surveys came directly to the university partners. Upon receipt of the data, the team created individualized reports for teachers that synthesized the cumulative data, disaggregated the data by different demographic categories (e.g., identification as student of color, languages, gender), and provided additional resources for teachers around improving the student experience in science.

The student surveys were coordinated with the teacher surveys, such that there would be overlapping constructs between the two sets of surveys (as shown in Table 4.1). Although the overlap was not perfect, it provided an opportunity to connect perspectives across important dimensions from both the teachers and the students they taught. The Interest Survey was given out the weeks in which the teachers were given surveys on equitable 3-dimensional instruction (version A) and formative assessments, phenomena, and student interest (version C). The Science Talk Survey was given out the week in which the teachers were given the survey on equitable discourse strategies (version B). For case 2, the study will show how middle school science teachers from CSD collectively made sense of the student practical measures (from both sets of surveys), and how this nudged the practice of collecting data around the student practical measures.

4.5.5 *Data Collection and Analyses*

The overall analytic approach to the data was in the form of case studies that describe the design of professional development sessions for science teachers (Yin, 2017). These case studies illustrate the interpretation and use of practical measures data, to show how this data can be leveraged to design professional learning opportunities for science teachers that is responsive to their needs and promotes changes in practice.

There were multiple data sources for this study: teacher and student practical measures, artifacts collected during professional development sessions (e.g., exit tickets, teachers' notes), and ethnographic field notes (using a participant-observer frame, Wolcott, 1999). The relevant data sources will be implicated throughout the cases, and their analyses will be guided by deductive themes from the conceptual framework and the inductive themes that emerged from the data analysis (Strauss and Corbin, 1994). Specifically, the analytical framework will be attending to sense-making perspectives brought to the interpretations of the practical measures data, linking these perspectives to design decisions around professional-development sessions for teachers, and capturing the multiplicity of teacher voices in the sense-making that occurred during the professional development sessions.

4.6 RESULTS

4.6.1 *Research question 1: How can practical measures be used to guide the design of professional learning experiences with high school chemistry teachers?*

Case 1: For the first research question, the data will be drawn from the teacher practical measures surveys from the high school chemistry teachers in BSD. The findings here will first talk about how the SEPC collaboratively made sense of this data, and then how this data was used to inform the design of the PD sessions.

The Partnership's Collaborative Sense-Making with Teacher Practical Measures Data

The case vignette presented here comes from the sense-making between Heena, university researcher and former chemistry instructor, and Athena, secondary science manager at BSD and a former secondary science teacher, around the teacher practical measures data. Heena and Athena had been working together for over a year in the first phase of the project. As the second phase of the project began, Heena and Athena partnered in the work, as it involved the chemistry teachers at BSD.

The data was synthesized by Heena and collectively made sense of by Heena and Athena. Together, the two shared their sense-making of the chemistry teachers' open-ended responses to the question, "what challenges did you encounter during three-dimensional instruction." For example, one teacher stated, "math is difficult for some students. Algebra is a challenge. Using calculators properly is a challenge. Reporting numbers with sig figs and units remains on the list of on-going teachable moments." Another teacher stated, "trying to cover basic chem with often limited math skills." As Heena and Athena were reviewing the teachers' open-ended responses, they noticed that the teachers were frequently describing students' mathematical abilities as a challenge that they encountered in instruction. As Heena and Athena deliberated over this data, they each brought forth their respective experiences that were relevant to sense-making around this data.

Heena noted that there have been numerous studies in the chemistry education research literature that have shown that students' have a dissociation between algorithmic and conceptual understandings of various chemistry topics (e.g., ideal gas laws), where students tend to have an understanding of the algorithm but not the underlying chemical concepts (Cracolice, Deming, and Ehlert, 2008; Sanger, 2005). Additionally, research has shown that students' algorithmic understandings can mask conceptual understandings (McDermott, 2015). Thus, she concluded that it was important to support the chemistry teachers to attend to students' conceptual understandings not just their algorithmic understandings in the PD sessions. Here, Heena is leveraging her knowledge of the chemistry education research literature in this conversation, as it is pertinent to the data under discussion, and using it to make a claim about how it informs the design of PD sessions.

Athena also noted that chemistry teachers, in her experience, tended to privilege students' algorithmic skills and that teachers often mentioned that students struggle with these sets of skills and so should not be taking chemistry classes. She stated that she wanted to disrupt this narrative, and to help support teachers to see the conceptual perspectives that the students can bring to sense-making in chemistry.

The practical measures data made visible teachers' experiences and perspectives around students' mathematical skills in chemistry contexts. Heena and Athena then engaged in perspective-making, whereby they were each able to bring their expertise and experiences to bear as they were reasoning around the practical measures data, with Heena drawing on her knowledge from the chemistry education literature and Athena drawing on her experiences with chemistry and science teachers. Thus, they offer unique, complementary, and important perspectives on this data, which also yielded convergence on the action of designing a PD session that would support teachers to see the conceptual resources that students bring to sense-making (the design of the sessions will be described in more detail in the next section).

In Heena and Athena's conversation, their interpretation of the practical measures data enabled each one to mobilize knowledge that helped in sense making around the data. Thus, the practical measures served as a boundary object that facilitated perspective making (a dialogical learning mechanism) by enabling participants from two different sociocultural communities, research and practice, to make sense of the data from their respective communities. Through this process, they were able to achieve convergence on a design principle for the upcoming PD sessions, which will be formally described in the next sessions. As this case vignette shows, boundary objects enabled continuity in interaction, which enabled the SEPC to "combine ingredients from different contexts to achieve hybrid situations" (p. 319, Engeström et al., 1995). As Star & Griesemer (1989) note, boundary objects "become strongly structured in individual site use" (p. 393). Thus, the perspective-making by the SEPC, shaped the interpretation of the data which then lead to the design of the PD sessions.

Teacher Practical Measures Data Informing the Design of Professional Development Sessions

As Heena and Athena continued to make sense of the practical measures data from the chemistry teachers, Heena and Athena began to brainstorm the sessions for the next PD. They both wanted to draw teachers' attention to students' conceptual understandings in chemistry, given that the data showed that the teachers tended to focus on the students' lack of mathematical understandings. Additionally, Athena noted that each school had different chemistry curricula and teachers with a range of years of experiences in teaching chemistry (from 1, to more than 5 years), thus it was important for the sessions to be able to allow teachers to engage in collaborative sense-making where they drew on the experiences of the collective.

This then led Heena and Athena to identify two pertinent sessions (amongst others) for the upcoming PD: support teachers to (1) identify students' conceptual and algorithmic forms of expression on an assessment task, and (2) identify instructional responses based on students' facets of understanding (Minstrell, 1989; NRC, 2000). To support teachers in this process, Heena and Athena co-designed and ultimately enacted PD sessions that would attend to these objectives.

For the first objective, support teachers in identifying students' conceptual and mathematical understandings on a task, a grid (as shown in figure 4.1) was developed to help teachers make sense of each of these understandings for selected student work. The selected student work was from the lesson plans that the teachers co-designed during the summer PD, thus, the teachers had or would be implementing in them in their own classrooms. The student work was a set of entry and exit tickets, which consisted of the same questions; the questions contained both conceptual and mathematical questions. The entry and exit tickets are the same assessments that are discussed in chapter two, but are referred to as pre- and post-assessments in that context. The teachers were asked to assess overall growth in conceptual and mathematical understandings. Figure 4.2 shows the sense-making that a chemistry teacher engaged in with the grid. Additionally, teachers were asked to reflect on the following questions: for the students who understood the mathematically-oriented questions, did they also understand the conceptually-oriented questions? And vice versa?

This session attended to understanding students' symbolic level of representation in the chemistry education framework (Johnstone, 1993), which involves the use of symbols, equations, and mathematics in sense-making around chemical phenomena. Prior research has shown extensively that students tend to do better on the algorithmic aspects of a question as compared to the conceptual aspects (Nurrenbern and Pickering, 1987; Sanger, 2005; Cracolice, Deming, and Ehlert (2008)). Chapter two talks about the research in this area in greater detail. Professional learning experiences for teachers should emphasize the design of assessments and activities for chemistry that enable students to bring forth conceptual and mathematical ways of thinking, both separately and in integrated ways, as appropriate.

	Entry Ticket		Exit Ticket		Growth
Student	Mathematical Understanding	Conceptual Understanding	Mathematical Understanding	Conceptual Understanding	

Figure 4.1 Grid developed by the SEPC to support teachers in making sense of students' conceptual and mathematical understandings for a specific piece of student work.

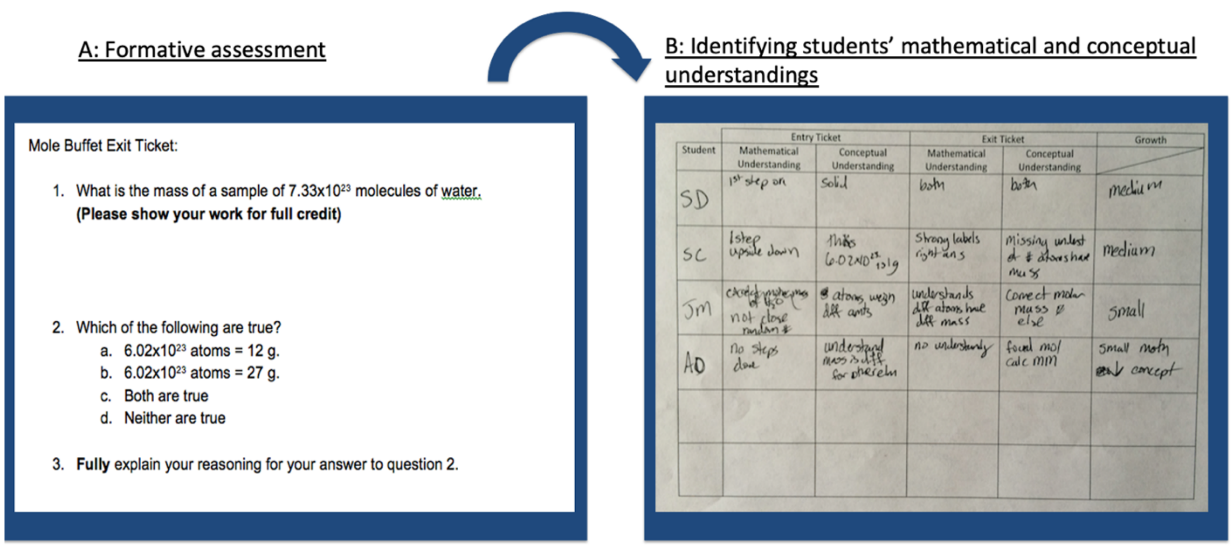


Figure 4.2 Chemistry teacher sense-making around students' mathematical and conceptual understandings (B) based on their entry/exit ticket responses (A).

For the second objective, identify instructional responses based on common facets of understanding that students need to refine, teachers were asked to identify facets of thinking observed in students' conceptual and mathematical ideas and strategies around the activity, and to identify the next steps of instruction based on these facets. For example, one teacher said that a common facet observed was students' thinking that "1 mole = 1 gram." Teachers then brainstormed the next steps of instruction based on this facet, including "use side-by-side comparison of different examples where there are two substances and the students have to figure out which one contains one mole" and "have students measure out one mole and then explain their process." First, in the observed facet, teachers are noting that students are assuming that the quantity statement (as described in chapter 2),1 mole = 1 gram, is always true. The teachers then brainstorm a couple of instructional moves that they can make to respond to this facet. This process occurred for a variety of student facets, with moving away from the notion of students' ideas as misconceptions, and as a resource for the next steps of instruction. Through this session, teachers discussed ways that they can engage in informal formative assessments on specific student facets, whereby teachers interpret and act on the ideas that are contributed by students (Araceli Ruiz-Primo and Furtak, 2006). In this process, students' ideas are serving as resources, for which the students to expand on their thinking in productive ways.

The two sessions for the chemistry teacher PD were complementary in nature. The first session asked the teachers to think about, what are students are conceptual and mathematical facets, and the second session asked, how can these facets be leveraged in instruction. Collectively, these sessions highlight the role of designing assessments and activities that engage students' mathematical and conceptual ideas of a topic, and then leveraging these ideas in the next steps of instruction. Thus, the practical measures data from the chemistry teachers provided situated data which could be leveraged to design improvement efforts that were responsive to the needs of the teachers (Bell, et al., in preparation). Through the practical measures data, the SEPC was able to make sense of the teachers' experiences, mobilize knowledge from their respective communities that helped in the interpretation of the data, and design sessions that were responsive to the teachers' needs and the goals of the partnership.

4.6.2 *Research question 2: In what ways can professional development support teacher sense-making and learning by collecting data around the students' experiences in the science classroom?*

Case 2: For the second research question, data will be drawn from the student practical measures surveys from the middle school science teachers in CSD. The findings here will first talk about how the teachers collaboratively made sense of this data, and then how the practice of collecting data around the students' experience was incorporated into the design of future PD sessions.

Teachers' Collaborative Sense-Making with Student Practical Measures Data

The research + practice partnership, the SEPC, intentionally had the design objective to support teachers in expanding their practices of formative assessment as not just attending to students' science content knowledge but also their experiences in the science class. Thus, the team developed a set of practical measures for students that were aimed at understanding the student experience in science class. The surveys began around November of 2017 and continued throughout the school year. When designing for the April 2018 PD for approximately 65 teachers, the SEPC wanted to bring the data collected around the students' experiences in the science classroom. At this point, five teachers from the CSD had administered the student practical measures, yielding approximately one-thousand student responses across the surveys.

The SEPC team designed a session entitled, "Understanding the Student Experience: In their Own Words." In the session, the SEPC explicitly identified three objectives for the session: 1) Share the Data from the Teachers and Students in the District, 2) Make Sense of the Student Data, and 3) Reflect on the Students' Experiences. The SEPC, prior to the presentation, had thematically sorted the students' responses, which were inductively derived from the students' responses to the questions: 1) how they did/didn't find science class interesting and 2) how they found whole class discussions in science class to be helpful/not helpful to their learning experience. The questions and emergent themes are below; table 4.2 provides sample responses for the themes.

How were the activities in science class interesting to you?

- Social Nature of Science/Hearing Others' Perspective
- Interest in Content
- Science Can Help Solve Problems
- Epiphanies

Why were the activities in science class not that interesting to you?

- Lack of Interest in Science
- Lack of Hands-On Activities
- Lack of Interest in Science Content
- Comments on Current Class Activities

In what ways does whole class discussion help you learn?

- Learning from Others
- Desirable Sociable Dynamics
- Engage in Learning Related Tasks

What is not helpful to you during whole class discussion?

- Undesirable Social Dynamics
- Personal Reflections

Table 4.2 The themes and students' sample responses to the questions on the student practical measures.

Question	Theme: Sample Response
How were the activities in science class interesting to you?	**Social Nature of Science/Hearing Others' Perspective:** "It was interesting to see what my peers thought about rock transformations on Venus." **Interest in Content:** "They deal with diseases that don't have a cure, which I find interesting." **Science Can Help Solve Problems:** "It was interesting because we got to design food that people in areas hit by hurricanes could eat." **Epiphanies:** "I never knew there were such things are mutations in real life."
Why were the activities in science class not that interesting to you?	**Lack of Interest in Science:** "Because science is not something I have enjoyed learning about it doesn't interest me at all." **Lack of Hands-On Activities:** "Because they were done on a computer and were not hands on labs." **Lack of Interest in Science Content:** "I'm not very interested in rocks in general." **Comments on Current Class Activities:** "It was kind of boring to just read and annotate the whole class, we hardly interacted with our team."
In what ways does whole class discussion help you learn?	**Learning from Others:** "I can change my perspective of things by listening to other students' ideas and I can also get ideas that can help me in what to say when sharing my thinking." **Desirable Sociable Dynamics:** "It helps all of us to want to share their ideas." **Engage in Learning Related Tasks:** "It helps me see new ideas that I didn't think about before."
What is not helpful to you during whole class discussion?	**Undesirable Social Dynamics:** "It is not helpful when a student just cut a student when they talk, it make me feel confusing." **Personal Reflections:** "I don't like to talk in from of the whole classroom."

The teachers were shown 3-5 responses for each theme, given time to reflect on it individually, in their table groups, and then in the PD group. After the end of the presentation, teachers were given an exit ticket, in which they were asked to reflect on the following questions: 1) Do you collect data on the student experience? If so, how do you incorporate it into your teaching practice? 2) What supports do you need to collect data on the student experience? 3) What are 1-2 takeaways from this session?

The data from the exit ticket were aggregated and analyzed, and the themes and sample responses are provided in table 4.3. Sixty-five teachers attended the session and filled out the exit tickets. The following categories emerged from their responses to the questions on the takeaways from the session: reflections on data provided in the PD, value of collecting data, and doing surveys. About one-third of teachers provided their reflections on the data (i.e., the students' self-reported experiences) that was presented during the session. There were a range of reflections around the students' self-reported experiences, where some teachers were using the students' reflections and connecting it to their practice, past and future. For example, one teacher reflected that the students' words reminded them of how students can experience whole class discussions in science. Another teacher reflected on a student's comment that there is pressure to share during all-class science discussions, saying "there's truth in that and I will remember that thought." In the first comment, the teacher is connecting what they observed in the students' responses to their own experiences; in the second comment, the teacher is connecting what they observed to future enactment. Thus, the student practical measures data is engaging the teachers in perspective-taking, in which they are taking the other into account, in light of their own perspectives (Boland and Tenkasi, 1995; Akkerman and Bakker, 2011). This is also reflected in the other responses where 29% of teachers express the value in collecting data around the student experiences in science class, and 10% are more explicitly stating that they want/need to do the survey. These are examples of dialogical learning occurring at the boundary, whereby the process of reflection-taking is resulting in an “expanded set of perspectives and thus a new construction of identity that informs future practice” (p. 146, Akkerman and Bakker, 2011). In the context of improvement science, the responsive changes are being informed and guided by the data (Bryk, et al., 2015). As one teacher states, “there were valuable learnings and I want to survey my students more often.” Through the teachers’ engagement with the students’ experiences, it is supporting them to see the value and importance in collecting data that can help them see their students’ experiences in science class. The next section will talk about how teachers’ practices shifted after this PD session.

Table 4.3 Themes from the teachers' takeaways from the April 2018 session (N=65).

Theme	Sample Responses
Reflections about the data presented (32%)	• Many students in the same room are having wildly different experiences • I'm reminded of how students experience talk activities in a whole class setting • I liked the quote "there's pressure to share but then nobody cares what I have to say." There's truth in that and I will remember that thought.
Value of collecting data (29%)	• Student voice is important to teach better and have better outcomes in student's learning • Usually, I just get data about how I am doing as a teacher. I like this better. • It helps to hear what kids have to say and verifies what work is being done • I want to do this more I need support
Do the survey (10%)	• I should have my students complete the students survey more often. • I need to be more intentional about this kind of data. • There were valuable learnings and I want to survey my students more often

Nudging Teachers' Practice with Collecting Student Practical Measures Data

The data from the student practical measures was presented during the April PD session. This data reflected the student voices from the classrooms of 5 middle school science teachers. After the April PD session, the number of teachers who had their students take the student practical measures more than doubled from the original number (i.e., 7 new teachers) within three weeks after the PD presentation of the data; by the end of the school year, this number had tripled (i.e., 15 teachers in total). Another set of student surveys was co-designed by the SEPC, which consisted of multiple constructs around students' learning and views around equity, identity, and dispositions towards science. This second set of surveys is intentionally being called a survey and not practical measures, as they it was not a short survey meant to engage in the moment experience, rather it was meant to capture students' reflections over the course of the entire year of instruction. This survey was administered around the middle of June. A total of 61 middle school science teachers administered this survey to their students, resulting in a total of 4,486 student voices. Thus, through the course of the year, more teachers began engaging in the work of implementing student practical measures and surveys to their students. Where there was a three-fold increase in the number of teachers administering the first set of practical measures to their students, and an even larger number of teachers doing so in the second set of surveys. Thus, from the initial April PD presentation around the students' experiences in the science class, to mid-June, teachers were "nudged" to engage in the work of collecting data around the student experience. The research literature in psychology has shown that the act of measuring behavior can bias respondents to attend to these behaviors more in the future (McCambridge, 2015; Godin, et al., 2012). While the teachers involved in the PD were not asked a specific set of questions over the course of the PD, the act of collecting and making sense of the data around the student experience in science became an important feature of the PD work, and the number of teachers who administered the first set of practical measures tripled from the initial number (i.e., from 5 to 15), and 61 teachers became involved in collecting data around the student experience in the second survey. Thus, the coherency in PD around this objective helped to encourage the practice. This process is similar to the documented effect of posing specific questions in a practical measures survey leading to more attention to those behaviors (Bell, et al., in preparation).

The data from the second survey was synthesized by the research team and individualized reports were given to teachers on the aggregated student responses around various dimensions of the students' experiences in the science classroom. It is important to note that the synthesis of the data occurred by the research team, as the student data was tied to the teachers, so the data coming to the university team was intentional so that teachers would not feel uncomfortable with the identified data being shared with the science district staff. During a five-day August Institute, teachers collectively made sense of the reports around the students' perspectives. In addition to the individualized student reports by teacher, the research team created graphs of how students across the entire district responded to the questions on the survey (as shown in figure 4.3).

These sessions during the PD gave teachers an opportunity to collectively reflect on the students' experiences across the entire district as well as their own classrooms. The teachers were given a set of prompts to support them in their sense-making of the students' data, including: what do I notice about the data, what surprises you about the data, what does not surprise you about the data, and what commitments can I make in the upcoming year to improve student learning experiences. The teachers collaboratively went through these questions for the overall student data, and individually, for their own students' data.

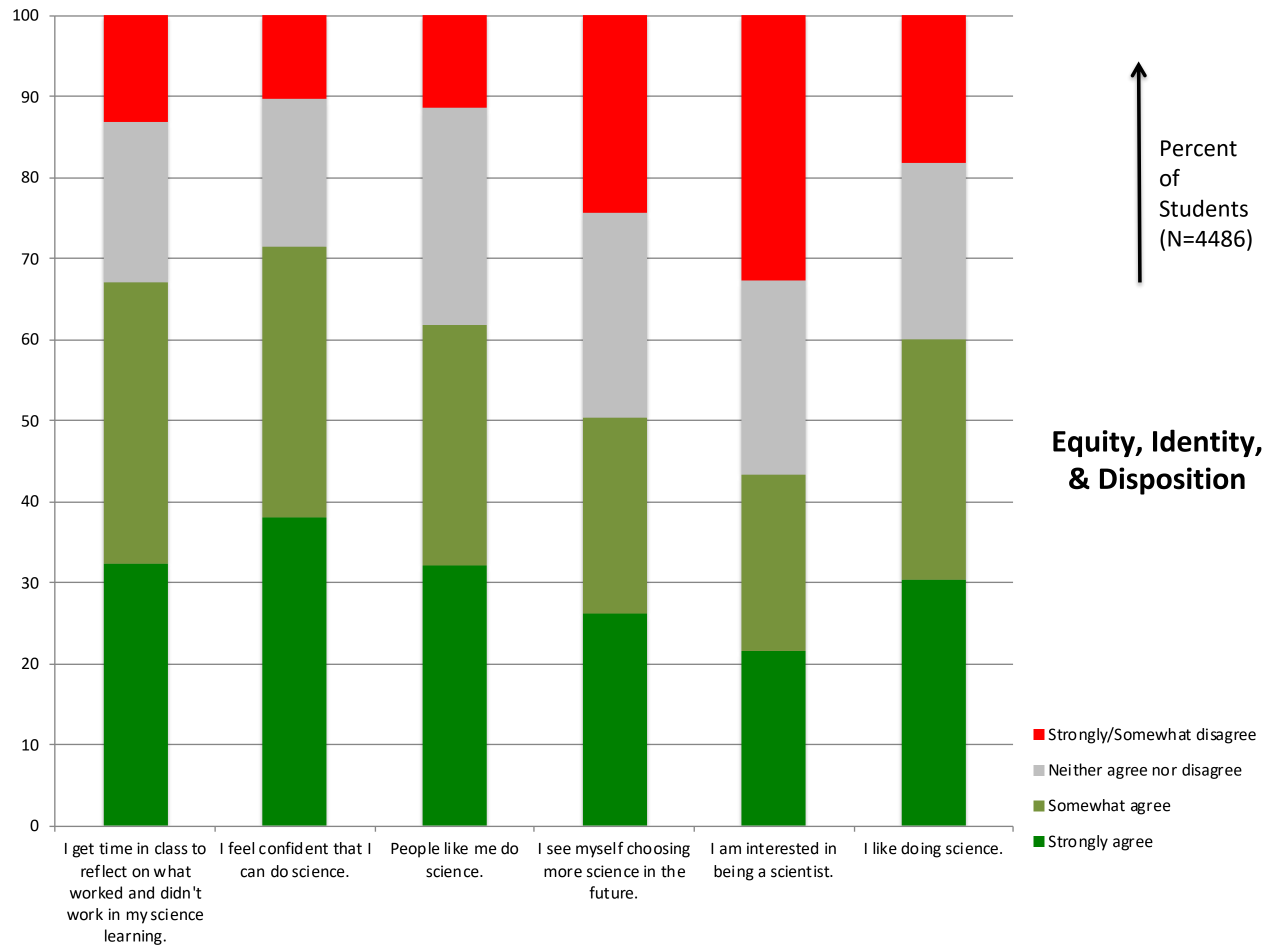


Figure 4.3 The students' responses to various questions around equity, identity, and disposition from approximately 4,500 students across CSD.

At the end of the August Institute, the teachers were asked a series of questions about how the sense-making with student data sessions on making sense of data around the student experiences went well and could be improved. The teachers were also asked in what ways they would integrate classroom data into assessment work. The illustrative themes from these questions are presented in table 4.4. Teachers identified the themes of having reflection time and identifying levers of impact as helpful components of the sense-making with student data sessions. These are processes that teachers engage in through traditional formative assessments, whereby it is a "process used by teachers and students to recognize and respond to student learning in order to enhance learning, during the learning (p. 536, Bell and Cowie, 2001)." The purpose of formative assessment is to integrate the existing knowledge and incoming information (Bell and Cowie, 2001), therefore providing continuity and connection between students' ideas and instruction. Formative assessments must be expanded to also include collecting data around students' experiences, however teachers need additional supports to do. As they note, they need more collaborative time and strategies to make sense of the large amounts of data. Finally, teachers noted that through collecting data on the student experience, they are hearing their students' voices, they are wanting to involve their students' voices in their instruction, and that through this process, it can help them form relationships with their students. Thus, teachers are viewing the process of collecting data on the student experience not only from a formative assessment lens, but from a lens of caring, whereby they are seeking to build relationships with their students (Bang, et al., 2016).

Table 4.4 The illustrative themes from the questions given after a session in which teachers collaboratively made sense of students' responses across the district and individually made sense of their own students' responses.

Question from August 2018 Summer Institute	Unique Themes - Illustrative example in "teacher voice"
What worked well in reviewing data from classrooms?	• ***Reflection time*** – "I really appreciated having so much quiet think time for myself to process the data before having a discussion with my table." • ***Identifying levers of impact*** – "Going from small group preliminary noticings and progressing to points of improvement that are important to us as educators in this district." • ***Hearing the student voice*** – "It was good to get student feedback about how they feel about science."
How could we improve in helping you work with data from your classroom?	• ***Reflection time*** - "...continue to give us time to reflect and think about the data that we collect in our classrooms…." • ***Collaborative sensemaking time*** - "...allow us time to work with teachers and also the lead teachers so that we can realize the full potential of what the data can tell us and how we can use the data to drive our instruction." • ***Strategies for making sense of the data*** – "At this time, I feel I have SO much data, I just need a means to sort it efficiently and utilize it quickly."
How are you going to integrate data analysis into your classroom assessment work?	• ***Adjusting future lessons*** – "I think it is important to ask students at the end of lessons and units if they learned the information and what helped them learn. Then taking that data and adjusting further lessons and units to meet the needs of all students. • ***Prompts to collect data*** – "I am going to post the teacher and student data questions above my classroom desk as a daily reminder of how to approach each day and as a guiding tool in developing assessment." • ***Forming relationships with students*** – "looking at how students reflected on interactions with me will help me improve my routines in the classroom and how I form relationships with students." • ***Leveraging student voice*** – "I want to involve more students' voices and self-reflection."

4.7 Conclusions and Implications

In each of the cases shown in this study, there were two processes that occurred with the practical measures: 1) collective sense-making around the data and 2) co-design of learning experiences with and around this data. The first case involved the SEPC reasoning about the teacher practical measures from the high school chemistry teachers. As the SEPC made sense of the data, they engaged in the dialogical process of reflection in the form of perspective-making, where they mobilized knowledge to make sense of the data from their respective sociocultural communities (Akkerman and Bakker, 2011; Boland and Tenkasi, 1995). This made visible multiple perspectives around how to make sense of the that involved both researcher and practitioner perspectives. The SEPC then leveraged these conversations to design PD sessions for chemistry teachers that leveraged their shared vision for the chemistry teaching. The shared vision involved supporting chemistry teachers to attend to students' conceptual and mathematical understandings, as well as to leverage and build on their facets (for each of these understandings) over the course of instruction. This was accomplished through joint sense-making of student work from artifacts that were co-developed during an earlier PD session. Thus, this design leveraged a collaborative stance in sense-making of student work, with coherence along multiple dimensions, which involved the co-design of student artifacts and lessons, and teachers' own observations and reflections being centered in the analysis and interpretation of the student work generated from the co-designed lessons. Through these sessions, teachers were supported in differentiating and appreciating students' conceptual and mathematical understandings around chemical dimensional analysis, and to attend to students' facets of thinking and how to leverage them in the next steps of instruction.

The second case involved the middle school science teachers jointly making sense of the data from the student practical measures. This data preserved the student voices and thus, allowed teachers to see the students' experiences, in their own words, and was made sense of at multiple levels (individual, groups, district). The practical measures data enabled teachers to engage in the dialogical mechanism of perspective-taking, where one is taking the others' perspectives into account (Boland and Tenkasi, 1995) and to let this perspective inform future practice. Some teachers reflected on how the student practical measures data informed their perspectives on the value and the importance of collecting this data. Additionally, this resulted in teachers' shifting practice, where the number of teachers collecting data using the survey developed by the SEPC tripled by the end of the school year, and with 61 teachers collecting data on other dimensions of the student experience (approximately, 4,500 student voices were captured in this data), making sense of this data, and thinking about future opportunities to collect this type of data in their own practice. These actions by teachers, show how PD sessions were leveraged to nudge teachers in the practice of collecting and making sense of the data around the student experience throughout the course of the school year. In their reflections on this process, they not only started thinking of this from a formative assessment perspective, but also from a lens of caring, where they seeking to build relationships with students. Furthermore, in these PD sessions, the teachers were at the center of sense-making and responding to district-level and classroom data. In other models of data-driven decision-making, educators are not part of this process; rather it is a top-down data-driven implementation model that informs teaching practice "at a distance" (Shepard, Penuel, and Davidson, 2017). In the current model, the teachers being able to make sense of their own students' experiences enabled them to connect with their students' voices and to use it to inform their teaching practices.

In the cases presented in this study, the practical measures served as a boundary object that enabled dialogue across different socio-culturally distinct places. The data made visible different aspects of teachers' reflections around student learning and the students' experiences in science class. And the design of PD sessions leveraged this data to support practices that leveraged and built on students' ideas in instruction, and promoted collecting data around the student experience in science class, respectively.

Practical measures are a sensing mechanism that can provide a bridge between between socio-culturally distinct communities in a way that can guide the work of each of them in a coordinated manner. They are a fundamental aspect of meaning making as they can support continuity in interaction and learning. Akkerman and Bakker (2011) note, "dialogical engagement at the boundary does not mean a fusion of the intersecting social worlds or a dissolving of the boundary. Hence, boundary crossing should not be seen as a process of moving from initial diversity and multiplicity to homogeneity and unity but rather as a process of establishing continuity in a situation of sociocultural difference." Professional communities, when designing around making sense of practical measures data in a collaborative stance, are leveraging the collaborative and coherent principles of effective features of PDPs (Luft and Hewson, 2014; McDonald, Kazemi, and Kavanaugh, 2013; Putnam and Borko, 2000). Through the execution and interpretation of practical measures, the design of professional development sessions was able to leverage teachers' and students' experiences and voices, respectively, in the PD space that was contextualized, adaptive, and responsive to their needs.

The present study leveraged practical measures not as a form of monitoring, rather as a sensing instrument to understand and make meaning around teachers' and students' experiences in the science classroom. Thus, practical measures can serve the purpose of making visible not only content and practice-focused strategies, but other aspects of the work of science teaching experiences. When designing practical measures, it is critical to ask: whose perspective is involved and what dimensions of the learning experiences are being reflected. It is opportunity to provide voice to both teachers and students about inequitable situations and to provide ongoing contextual data to guide equity focused improvement efforts (Bell, 2019; Bell, et al., in preparation; Penuel, Bell, and Neill, 2020).

Chapter 5. CONCLUSIONS AND IMPLICATIONS

The studies presented in this dissertation show how mediating objects can support reasoning around the different representations in the chemistry education framework and the students' experiences in the science class. While each of these mediating objects were situated in different contexts and focused on different learning objectives, they were leveraged to support sense-making around the different representational levels in chemistry, including the student experience in science.

Through activity, learners come together to make meaning with mediating objects through social and/or material interactions (Cole, 1998). The first two studies looked at two key outcomes with the mediating object: 1) how sense-making was supported (which was defined as a process outcome) and 2) how the development of representational competence was developed (which was defined as a representational process outcome). The representational process outcome, as defined in a chemistry context, is the ability to understand a specific level of representation in chemistry (e.g., macroscopic, sub-microscopic, and symbolic levels), and to connect the levels, when appropriate. As figure 5 shows, the mediating objects served a dual purpose: meaning-making to understand disciplinary ideas (left triangle) and applying disciplinary ideas to chemical scenarios and phenomena (right triangle).

The first study investigated how a cognitive tool can support students' sense-making around quantities and quantity relationships during chemical dimensional analysis. The quantities (e.g., mass, moles, number of particles) that students reason about in a chemistry class are foundational for reasoning flexibly between macroscopic and sub-microscopic quantities.

The study observed a group of students make sense of the tool that made explicit the quantities and quantity relationships involved in chemical dimensional analysis, while they were reasoning about a specific chemical problem. As a group, the students were able to engage in meaning making around both conceptual (i.e., qualifying the differences between the quantities: moles and molecules) and algorithmic (i.e., understanding of the appropriate operations, quantities, and quantity relationships needed to convert from moles to molecules) aspects of chemical dimensional analysis. Thus, the social and material interactions with the tool supported students to clarify their emerging conceptual and algorithmic questions about chemical dimensional analysis.

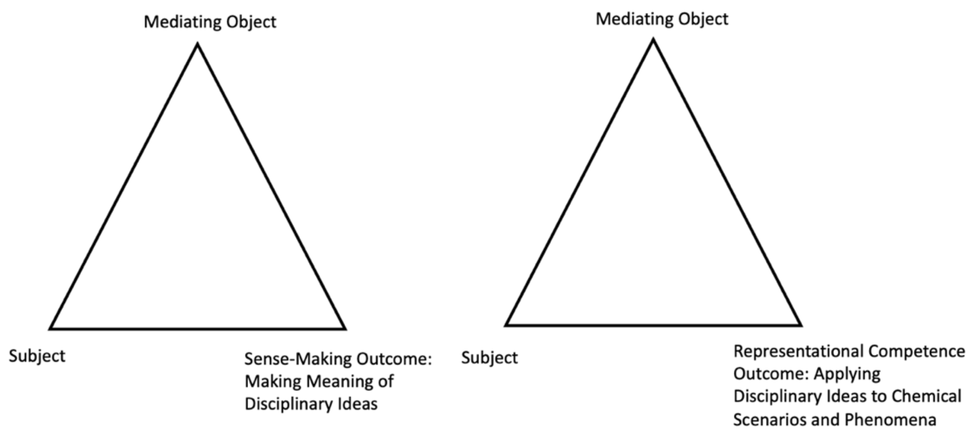


Figure 5 The role that mediating objects play in meaning-making to understand disciplinary ideas (left triangle) and applying disciplinary ideas to chemical scenarios and phenomena.

The study also analyzed 23 students' pre- and post-assessments to understand whether they understood the algorithmic dimensions of chemical dimensional analysis, in which the students were able to use the tool during the assessments. The study found that none of the students were able to set-up the appropriate quantities and quantity relationships in the pre-assessment, whereas 83% of the students were able to do so in the post-assessment. Thus, the activity around making sense with the tool supported students to become proficient in identifying and setting-up the appropriate quantities and quantity relationships in chemical dimensional analysis.

The understanding of chemical dimensional is part of the symbolic level of representation in chemistry. It is fundamental to reasoning about other chemical ideas (e.g., chemical reactions) as well as a level of representation that should be understood in of itself (Johnstone, 1993; Talanquer, 2011). In this study, the tool supported students in their navigation of their meaning making around chemical dimensional analysis, by making visible the quantities and quantity relationships in chemical dimensional analysis, through coordinated social and material interactions. Thus, tools and activities should be designed with the purpose of supporting students in sense-making around the variables (in this case, quantities and quantity relationships) involved in the representational/symbolic understanding of chemistry and in science.

The second study was interested in understanding how students' understanding of the sub-microscopic account of a chemical phenomenon can help students make sense of the macroscopic/observed phenomenon. In the study, it investigated how conceptual sketching affects students' explanations of chemical events at the sub-microscopic level, and how students represented the interactions in a chemical phenomenon in their sketches as compared to their causal explanations. The study found that students in a sketching group were more likely to represent the appropriate interactions between the substances in a chemical phenomenon, as compared to students in the non-sketching group in their explanations. Furthermore, the students in the sketching group were more likely to invoke particulate-level interactions in their explanations as compared to the non-sketching group. Interestingly, for the students in the sketching group, they were more likely to invoke the particulate-level interactions in their sketches as compared to their explanations. Furthermore, in their explanations, the students in the sketching group were more likely to connect the sub-microscopic/particulate account back to the macroscopic/observed levels, as compared to the non-sketching group. Thus, through conceptual sketching, students were more likely to "see" how the sub-microscopic interactions were supporting the observed behaviors.

Through these sets of findings, the mediating object supported students to visualize and represent the substances and the appropriate interactions amongst them. This has been shown in other studies, in which computer-mediated visualization of a chemical phenomenon can support students to have an increase in conceptual chemical understanding at both the high school and undergraduate levels (Ardac and Akaygun, 2004; Russell, et al., 1997). Thus, through visualization, the students are being able to engage and manipulate the "elements" that are present in the phenomenon. Furthermore, it is important to note that the students are using their conceptual sketches and their explanations in complementary ways, whereby the sketches can make explicit the particulate-level interactions, and the explanations can provide the connection between the sub-microscopic account to the observed behavior. The conceptual sketches provided a medium for the students to make meaning of the phenomenon, and to gain more experience with using material and conceptual tools to support their engagement with it. As a student noted in their reflection about the conceptual sketches, "to have a visual representation of what was happening and would be easier to explain." Thus, the conceptual sketching supported students to visualize, make sense, and explain the phenomenon. The conceptual sketching is not just a part of the suite of tools that chemists use to make meaning (Kozma, 2000), but it is also a way to support students in making the connections between the macroscopic and sub-microscopic levels of representation of a chemical phenomenon (Stieff, 2011). Thus, activities should be designed that allow students to make sense of phenomena through both explanation and conceptual sketching/modeling to support them in connecting the macroscopic and sub-microscopic accounts in chemistry and in science.

The third study looked at how practical measures served as a boundary object in the context of professional learning session for high school chemistry and middle school science teachers. The practical measures facilitated two process: 1) collective sense-making around the data and 2) co-design of learning experiences with and around this data.

In the case with the high school chemistry teachers, the practical measures enabled the SEPC team to mobilize knowledge from their respective communities to make sense of this data; thus, engaging the dialogical learning process of perspective-making (Akkerman and Bakker, 2011; Boland and Tenkasi, 1995). Thus, the practical measures allowed the research-practice partnership to make sense of what was being experienced by the teachers, bring forth their unique perspectives to make sense of this data, come to a shared interpretation of the data, and then leverage these processes to inform the design of the professional learning experiences for the chemistry teachers. In this case, the practical measures served as a boundary object, whereby it made visible the experiences of the chemistry teachers, and enabled the research-practice partnership to engage in the dialogical learning mechanism of perspective-making to interpret the data.

In the case with middle school science students, the practical measures enabled the middle school science teachers to engage in the dialogical mechanism of perspective-taking, whereby teachers were able to connect the students' reflection to their practice, past and future (Boland and Tenkasi, 1995; Akkerman and Bakker, 2011). Through their reflective processes, the teachers engaged in a an “expanded set of perspectives and this a new construction of identity that informs future practice” (p. 146, Akkerman and Bakker, 2011). This change in practice was observed as more teachers took up the practice of practical measures, where the number of teachers tripled by the end of the school year and 61 teachers engaged in collecting data around the student experience in another survey.

While teachers were engaged in making sense of students’ data from the second survey, the teachers identified, having reflection time and identifying levers of impact, as helpful processes to making sense of the student data. In their reflections, the teachers also began to identify elements of the formative assessment cycle in the ways in which they were thinking about collecting data around the students’ experiences in science, where they noted that through collecting data on the student experience, they are hearing their students’ voices, they are wanting to involve their students’ voices in their instruction, and that through this process, it can help them form relationships with their students. The teachers were thinking of the process of collecting and making sense of the data around the students’ experiences, not only from a formative assessment perspective, but one of caring, where they wanted to build relationships with their students. In this case, the practical measures is serving as a boundary object, whereby it is making visible the experiences of the students in the science class, and supporting the middle school science teachers to engage in the dialogical learning mechanism of perspective-making to interpret this data and to inform their future practice. Thus, in the design of professional learning experiences for practicing science teachers, practical measures should be leveraged to sense and support teachers’ current pedagogical practices and professional learning needs.

The studies, as laid out in this dissertation, talk about how mediating objects can de designed into different activity systems. As researchers and practitioners engage in the design of mediating objects, the following themes (which cut cross all scientific disciplines) should be attended to in the design of these objects.

First, the design and framing of mediating objects within activity systems should engage both disciplinary ways of thinking and meaning-making pathways. The studies presented in chapters two and three demonstrate how learners can use a mediating object within an activity system to engage in both representational thinking in chemistry and meaning making around chemical problem-solving and phenomena. To support learners in this process, it is critical that the disciplinary conventions and goals in representational thinking be made explicit in the framing of the activity system. For example, the study in chapter three showed that a higher percentage of the learners in the sketching group (as compared to the non-sketching group) connected the sub-microscopic account to the macroscopic observation when making sense of a chemical phenomenon, but this was true for only a quarter of the students. This may be because the learners were not aware that this was an important aspect to representational understanding in chemistry (Johnstone, 1993; Stieff, 2011). Thus, in the framing of activity systems, learners should be made aware of the framing of the task, such that it makes the epistemic goals visible to them (Lehrer, 2009).

The design of the mediating object elicits multiple metaphors of learning in its design. In the present studies, the mediating object both supported acquisition of representational competence and meaningful participation with the mediating object, through social and material interaction and participation. Sfard (1998) describes two “metaphors” that are used in the learning sciences: the “acquisition” metaphor and the “participation” metaphor.” The participation metaphor is also about becoming a participant in a community and engaging in key aspects of discourse and activity in this process. Through the engagement with boundary objects, participation is becoming transformed where students are learning how to engage in disciplinary ways of thinking (mathematical reasoning and conceptual sketching). Thus, learning does not occur only through participation; learning is also participation. The mediating objects can support both of these aspects of learning.

Second, the design of mediating objects and activity systems should recruit multimodal forms of participation to support deep conceptual understanding. In science, students are making sense of phenomena, for which to have a deep understanding, requires students to think about how the "invisible" entities are interacting (e.g., atoms, cells, forces, etc.). It is critical for students to have the opportunity to work with external representations both social and material in nature, thus enabling students to understand the conceptual ideas in a deep way and to also engage in the work of science. These material mechanisms do not always have to formal, like conceptual sketches. Students should be empowered to engage in "back of the envelope" sketching (as people engage in back-of-the envelope calculations when splitting a check), whereby they leverage external representation to make sense of how the invisible entities are behaving in phenomena. And this practice should be a part of sense-making of chemical concepts and phenomena in class. Through sketching, students can connect the macroscopic, sub-microscopic, and symbolic accounts, in which they are making sense of a phenomenon by invoking the representational levels of chemistry (Johnstone, 1993; Stieff, 2011).

Third, the design of professional learning experiences for practicing science teachers should enable them to develop interpretive power around students' conceptual understandings and experiences in the science class. In the professional development sessions described in chapter four, teachers came together to make sense of students' facets around a specific topic in chemistry in one setting, and to make sense of students' experiences in the science classroom in another setting. Through these sessions, the teachers became more attune to identifying different forms of conceptual and algorithmic understandings, and reflected and made sense around the plurality of students' experiences in the science classroom, respectively. Thus, the professional learning experiences supported teachers in exercising interpretive power, whereby they were "able to see new things and consider more alternatives, analyze students' learning more finely, and consider their practice more deeply and in more complex ways" (p. 16, Ball and Cohen, 1999). Thus, this interpretive power can disrupt narrow conceptualizations of disciplinary knowledge and work against deficit views of non-white children and communities (Rosebery, et al., 2008; Rosebery, Warren, Tucker-Raymond, 2016).

It is important to note that the cognitive and cultural foundations of learning need to be attended to both separately and together. While the study presented in this dissertation attended to conceptual facets of knowledge (from the perspective of disciplinary core ideas) and students' experiences separately, they can be weaved through culturally expansive sense-making in science instruction, which can expand meaningful opportunities to learn in in science. Bang et al., (2016) describe three principles that can expand meaningful opportunities to learn in science: notice sense-making repertoires, support sense-making, and engage diverse sense-making that this process. Thus, through culturally expansive sense-making, teachers and students approach scientific phenomena from varied perspectives and they navigate deeper connections between phenomena and their experiences (Bang, et al., 2016; Bell, et al., 2012). Thus, learning is about connecting students' prior knowledge (Rivet and Krajcik, 2008), interests, and identities in instruction (Bang and Medin, 2010; Warren, et al., 2001; Bell, et al., 2012).

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APPENDIX A

Questions for Chemical Phenomenon #1

Thinking about Monday's balloon activity... When you inflate the balloon, how would you describe and explain what is going on at the macroscopic and microscopic levels.

- How would you describe this process at the **macroscopic** (e.g., what you observe/experience) level? ____

- How would you explain this process at the **microscopic** (e.g., particulate, atomic or molecular) level? ____

Questions for Chemical Phenomenon #2

Please answer the following questions for the phenomenon that you just observed and sketched.

- Describe the behavior that you saw when the glass tube was placed in the yellow liquid. ____

- How would you explain this process at the **microscopic** (e.g., particulate, atomic or molecular) level using your understanding of intermolecular forces? ____

Questions for Chemical Phenomenon #3

Think about the following scenario. We place an egg with a semi-permeable membrane into a **hyper**tonic solution that consists of a thick and sugary corn syrup. We then remove the egg from the solution after 8 hours. Please answer the following questions for this scenario.

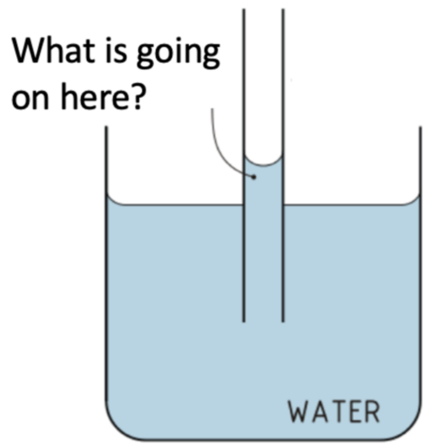
- What happens to the egg in this scenario? ____

- Use your understanding of osmosis and semi-permeable membranes to explain what is going on at the microscopic level (e.g., particulate, atomic, or molecular). ____

APPENDIX B

Conceptual Sketching for Phenomenon #2

First Name: ________________________
Last Name: ________________________



a) The adhesive forces in this phenomenon are

b) How would you represent the adhesive forces?

c) The cohesive forces in this phenomenon are

d) How would you represent the cohesive forces?

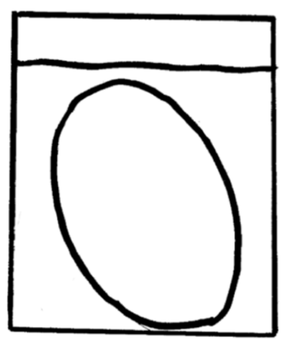
Conceptual Sketching for Phenomenon #3

First Name: ________________________
Last Name: ________________________

Scenario: We place an egg with a semi-permeable membrane into a **hyper**tonic solution that consists of a thick and sugary corn syrup. We then remove the egg from the solution after 8 hours.

1.What do you observe when the egg is removed from the solution?

2. Egg in the sugary corn syrup



Using arrows, show which particles are entering and/or leaving the egg. Be sure to label the the particles.

APPENDIX C

Teacher Practical Measures: Equitable 3-Dimensional Instruction Survey

Q1 Please enter your name

- ◯ First Name ____
- ◯ Last Name ____

Q2 What did you teach this week?

____

____

____

Q3 Which, if any, disciplinary core ideas (DCIs) did your students work on this week? (Select all that apply).

Q4 Which cross-cutting concepts (CCCs) did your students work on this week? (Select all that apply.)

Q5 Which science and engineering practices did your students work on this week? (Select all that apply.)

Q6 Briefly describe how you integrated the three dimensions in your instruction this week--Disciplinary Core Ideas (DCI), Science and Engineering Practices (SEP), and Cross-cutting Concepts (CCC).

____

____

____

Q7 Provide an example of something that went well with 3D instruction this week:

____

____

____

Q8 Provide an example of a challenge you encountered with 3D instruction:

____

____

____

Teacher Practical Measures: Equitable Discourse Survey

Q1 Please enter your name

○ First Name ____

○ Last Name ____

Q2 What did you teach this week?

____

____

____

Q3 Did you try out any discourse strategies in the past week?

○ Yes

○ I did not get a chance to try out any discourse strategies this week

Q4 If yes, which discourse strategies did you try? Please select all that apply.

- ☐ Three-stay-one-stray Link
- ☐ All-day post-its Link
- ☐ Idea Chips Link
- ☐ Agree-disagree line Link
- ☐ Discussion diamond Link
- ☐ All-class science talk Link
- ☐ Four quadrants Link
- ☐ Conceptual cartoons and share-trade Link
- ☐ Claim-pass Link
- ☐ Idea coaching Link
- ☐ Write & Pass Link
- ☐ Other: (please describe)

____

Q5 What percentage of students would you say were engaged during the discourse strategies?

Q6 What went well with discourse strategies?

- ☐ English language learners participated
- ☐ Students used evidence while sharing ideas
- ☐ Students listened carefully to each other
- ☐ Students responded to others' thinking
- ☐ Quiet students spoke more often
- ☐ Other (please describe)

____

Q7 What challenges did you encounter with discourse strategies?

- ☐ Some students didn't speak in class
- ☐ Some students dominated the conversation
- ☐ Some English Language Learners did not participate
- ☐ Students gave one-word answers
- ☐ Other (please describe)

____

Q8 Describe how you documented student thinking and/or engagement during discourse.

____

Q9 In the past week, how often did you work on structuring student-to-student communication by:

	Never	Rarely (1-2 times per week)	Sometimes (3-4 times per week)	Daily or almost daily	Several times per day
Making sure each student had equal opportunity to speak	○	○	○	○	○
Giving each student time to write their ideas before talking to them	○	○	○	○	○
Providing examples of ways students could phrase their responses, like sentence stems	○	○	○	○	○
Attending to students' multimodal ways of communicating (e.g., gesturing, drawings, etc.)	○	○	○	○	○

Q10 In the past week, how often did you have a chance to listen to students' ideas without "correcting" them by:

	Never	Rarely (1-2 times per week)	Sometimes (3-4 times per week)	Daily or almost daily	Several times per day
Using coaching talk moves, such as "Are you saying____?" even if the student didn't fully grasp the concept yet	○	○	○	○	○
Trying to keep my ideas to myself so I could fully understand what the student was saying	○	○	○	○	○
Trying to find students' "intellectual treasures" in their written work or in their talk	○	○	○	○	○

Teacher Practical Measures: Formative Assessments, Phenomena, and Student Interest

Q1 Please enter your name

○ First Name ____

○ Last Name ____

Q2 What did you teach this week?

____

____

____

Q3 Did you use formative assessment in your classroom in the past week?

○ Yes

○ I did not have a chance to use formative assessment this week

Q4 Which formative assessment strategies did you use? Select all that apply.

- ☐ Short tests of conceptual ideas expressed through disciplinary practices
- ☐ Brief exit tickets on students' conceptual ideas, engagement in practices and learning process
- ☐ Analysis of student work and performances (e.g., using criterion-based, leveled rubric, badges for micro-credentialing of competencies)
- ☐ Conversation with students about their thinking (individually, small group, whole class)
- ☐ Other (please describe)

____

Q5 Briefly describe the formative assessment you used this week--what did students do?

____

____

____

Q6 What went well with formative assessment this week?

- [ ] Students used evidence while sharing/describing ideas
- [ ] The assessment(s) was three-dimensional
- [ ] The assessment(s) included multiple modes (gesture, illustration, speaking, writing, etc)
- [ ] I had time to reflect on student work to understand how they're doing
- [ ] I used the formative assessment data I collected to make changes to instruction within the unit
- [ ] Other (please describe) ____

Q7 What challenges did you encounter?

- ▢ It was challenging for English language learners to complete assessments
- ▢ Students gave one-word answers
- ▢ We needed more time
- ▢ I did not have time to reflect on student work
- ▢ Other (please describe) ____________________

Q8 Formative Assessment Learnings

- ○ Briefly tell us what you learned from the data this week: ____________________
- ○ What were the change(s) to instruction you made: ____________________

Q9 In the past week, did your students investigate a specific phenomenon?

◯ Yes

◯ Not this week

Q10 What phenomenon did your students make sense of?

____

Q11 Were you able to incorporate students' experiences and/or interests in the phenomena?

◯ Yes

◯ No

Q12 If yes, how did you incorporate students' experiences and/or interests in the phenomena?

____

Q13 If not, how might you incorporate students' experiences and/or interests in the phenomena in the future?

____

APPENDIX D

Student Practical Measures: Science Interest Survey

Q1a What is the name of your school?

____

Q1b What is your teacher's last name?

____

Q1c Which period is your science class?

Q2 I worked on the following practices in my science class today... (please check up to **two** practices that you worked on today)

- ☐ using models to help me understand or explain something.
- ☐ using data as evidence to support a claim.
- ☐ putting ideas together to communicate them to others.
- ☐ collecting data for a science investigation.
- ☐ building a solution to a problem.
- ☐ analyzing or interpreting data from a science investigation.
- ☐ using mathematical ideas in my sense-making.

Q3 What specific activities did you do in science class today?

____

Q4 The work we did in science class today...

	Not at all	A little bit	A fair amount	A lot
was interesting to me.				
was like the work that scientists and/or engineers do.				
connects to something in my life.				

Q5 Why were the activities in science class not that interesting to you? (If the options "not at all" or "a little bit" are selected).
OR How were the activities in science class interesting to you? (If the options "a fair amount" or "a lot" are selected).

We are interested in your learning experiences. We would like to know a little bit more about your background, so that we can improve learning for you.

Q6 I identify as a student of color.

Yes

No

I don't want to say

Q7 I speak one or more languages at home, other than English.

Yes

No

I don't want to say

Q8 I identify as...

Female

Male

Nonbinary

Other

I don't want to say

Student Practical Measures: Science Talk Survey

Q1a What is the name of your school?

____

Q1b What is your teacher's last name?

____

Q1c Which period is your science class?

Q2 What specific activities did you do in science class today?

____

____

Q3 We are interested in understanding how talking went in science class today.

In science class today I.... (please check all that apply)

- ☐ was given the opportunity to share my ideas
- ☐ took the chance to share my ideas
- ☐ felt comfortable sharing my ideas
- ☐ had an opportunity to write about my thinking before talking
- ☐ felt like my peers and/or teacher listened to my ideas
- ☐ was able to express my ideas in more than one way (for example: writing, drawing, talking, gesturing)

Q4 Listening to other students helps me...

	Not at all	A little bit	A fair amount	A lot
improve my thinking				
see different perspectives on a topic				
improve my ability to argue with evidence				
learn how to communicate my science ideas more clearly				

Q5 I learn a lot better when we...

	Not at all	A little bit	A fair amount	A lot
talk in whole class discussions				
talk in small group discussions				
have time to think before we talk				
work individually and silently				

Q5a What is not helpful to you during whole class discussions? (If the options "not at all" or "a little bit" are selected).
OR In what ways does whole class discussion help you learn? (If the options "a fair amount" or "a lot" are selected).

Q5b What is not helpful to you while working individually and silently? (If the options "not at all" or "a little bit" are selected).
OR In what ways does working individually and silently help you learn? (If the options "a fair amount" or "a lot" are selected).

We are interested in your learning experiences. We would like to know a little bit more about your background, so that we can improve learning for you.

Q6 I identify as a student of color.

Yes

No

I don't want to say

Q7 I speak one or more languages at home, other than English.

Yes

No

I don't want to say

Q8 I Identify as...

Female

Male

Nonbinary

Other

I don't want to say

VITA

Heena Lakhani has worked as a chemistry instructor, developmental psychologist, and as an analyst for the National Science Foundation. She holds advanced degrees in Chemistry, Mathematics for Teaching, and the Psychological and Brain Sciences. These work and academic experiences lead her to pursue questions about teaching and learning that bring together conceptual and theoretical frameworks from discipline-based education research, science education, and the cognitive and cultural foundations of learning.