Pedagogical Content Knowledge and the Gas Laws: A Multiple Case Study

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Dedication

This dissertation is dedicated to my husband, Carlos Figueroa, and my parents, Lorraine and Gerry Sande.

To my husband, for his love, support and belief in my abilities to accomplish this goal.

To my mother, for her continued care of my person and nourishment of my spirit.

To my father, for his beautiful example of what a scholar should be.
Abstract

Pedagogical content knowledge (PCK) has been described as an assemblage of the most powerful analogies, demonstrations, examples and illustrations that make content knowledge understandable to students, together with an understanding of the preconceptions and alternate conceptions that students bring with them to the classroom (Shulman, 1986). In speaking of representations, Johnstone (1991) and Gabel (1993, 1998) suggest that there are three categories of representations in chemistry: the macroscopic, particulate, and symbolic. For the present study, a fourth category has been added, the graphic representation. In addition, Bell, Veal & Tippins (1998) proposed a hierarchy of PCK, a structure wherein the broadest concept (science PCK) is specified by discipline PCK (chemistry PCK) and finally by topic PCK (Gas Law PCK). The present study will investigate the apex of this hierarchy, the intersection of PCK and the specific topic of the Gas Laws. The Gas Law PCK Model was created to illustrate the intersection of subject matter knowledge for teaching and topic-specific PCK. Four chemistry teachers, each holding a degree in chemistry, who had taught high school chemistry for at least three years, and who had taught the Gas Laws during each of the last three years, were given an assessment of their subject matter knowledge for teaching regarding the Gas Laws. Two interviews were conducted to address Gas Law PCK, focusing on representations and student preconceptions and alternate conceptions. Findings of this multiple case study indicate that the participants’ subject matter knowledge for teaching, ability to move among representations, i.e. representational competence, and understanding of student alternate conceptions regarding the Gas Laws and how to address those conceptions were limited. Possible influential factors of curricula and lesson planning were also explored. Recommendations for emphasis on specific subject matter knowledge for teaching representations, representational competence, students’ alternate conceptions and how to address student alternate conceptions were explored for pre-service teachers and in-service teachers.
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CHAPTER ONE
RATIONALE

It seems that never before in education has more focus been placed on what teachers are doing in classrooms. With *No Child Left Behind* (2001) demanding demonstrated results of student achievement and in some school districts, tying teacher salaries to those results, research on what makes a good teacher is paramount. In addition, the *Race to the Top* (2009) program is also demanding more teacher accountability and demonstration of improved student achievement. While other documents such as the *National Science Education Standards* (1996) and *Project 2061* (1989) provide guidelines for science teachers regarding curriculum and instruction, *No Child Left Behind* and *Race to the Top* are prompting additional research into what is occurring in classrooms, how increased student achievement is being accomplished, and what characteristics of those successful teachers can be mass-marketed to all teachers (Ripley, 2010). In an effort to address characteristics of successful teachers, this study focuses on experienced chemistry teachers’ subject matter knowledge for teaching and pedagogical content knowledge (PCK), specifically representations and student alternate conceptions, with respect to the Gas Laws.

In investigating the knowledge base of teaching, few descriptions or analyses of teachers managing ideas in the classroom discourse are given (Shulman, 1987). In managing ideas in a classroom, a teacher must understand the content knowledge being taught, the pedagogy appropriate for the knowledge, and the learners and what they bring to the classroom. The nature of content knowledge within the discipline can be described by Schwab (1964); and the nature of content knowledge for teaching as an amalgam of
content knowledge, appropriate pedagogy and knowledge about learners can be described by Shulman (1987). Let us examine each of these two concepts in greater detail.

Let us address the first question: how might we describe or define a teacher’s content knowledge? Schwab (1964) defined a body of knowledge within the discipline as the facts, principles, concepts and theories of the discipline, how these elements are organized within the discipline (substantive structures) and what counts as evidence and proof in the discipline (syntactic structures). Thus, content knowledge includes not only the facts of a field, but also the organization and relationships of those facts as well as how new information (facts, concepts or principles) are treated in the field.

These facts, theories, and the manner in which they are organized are substantive structures. In addition, when new facts, concepts or principles regarding the behavior of gases are proposed to the discipline of chemistry, the manner in which the community of scholars within the discipline treats those new ideas constitutes the syntactic structures. Thus, content knowledge will be defined as the facts, theories, concepts, and principles of a discipline, its substantive structures and its syntactic structures.

While Schwab defined a body of knowledge for the discipline of science, we cannot safely assume that this definition accurately describes the content knowledge needed by teachers in high school classrooms. Teachers possess a specialized form of content knowledge for the classroom that is based on the academic discipline but is uniquely different (Deng, 2005). The content knowledge chemistry teachers use to teach in their high school classrooms may be different from that found in a more advanced academic setting.
While the teacher may have a thorough understanding of chemistry content knowledge appropriate to an undergraduate student in college, it is not necessary or appropriate to teach this content knowledge to his or her students in a typical high school chemistry classroom. Here we see the chemistry content knowledge taught in the classroom is different from that of the academic discipline of chemistry. While teachers, assuming they hold a B.S. in chemistry, have an undergraduate students’ understanding of the substantive and syntactic structures of the discipline of chemistry, they also possess the knowledge of what are the appropriate substantive and syntactic structures for teaching chemistry in a specific classroom. Let us then define this form of chemistry content knowledge, that is, the chemistry content knowledge taught in the classroom plus its related substantive structures and syntactic structures, as “subject matter knowledge for teaching.”

This transformation of subject matter knowledge for teaching involves the use of pedagogical knowledge—instructional practices, educational aims, knowledge of the learning process, knowledge of learners and classroom management skills, as well as knowledge of the broader context, that is, the teacher’s knowledge of his or her students, school and community. This mixture or amalgam of content knowledge, pedagogical knowledge and context knowledge has been gathered and summarized under the concept “pedagogical content knowledge” (PCK) (Shulman, 1986; Grossman, 1990; Gess-Newsome, 1999). Thus, subject matter knowledge for teaching is transformed by PCK into lesson plans so that students can work with the subject matter knowledge (Abell, 2007).
Since the naming of pedagogical content knowledge (PCK) by Lee Shulman in 1986, much of the last twenty years has been devoted to defining PCK and determining ways in which to measure it. However, most scholars agree that PCK includes the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that make it comprehensible to others and includes an understanding of what makes the learning of specific topics easy or difficult; the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons. (Shulman, 1986, p. 9-10).

PCK is a dynamic and encompassing construct. This study will examine the two critical aspects of PCK—PCK as representations of the subject and as the conceptions and preconceptions that students have of the subject.

Johnstone (1991) and Gabel (1993, 1998) specifically address the content knowledge for teaching chemistry in their groundbreaking work on chemical representations. Johnstone discusses three categories of representations: the macroscopic, the microscopic and the symbolic. However, there seems to be an inherent alternate conception with the use “microscopic representation.” The microscopic representation, where molecules, atoms, ions and subatomic particles are the focus, implies that by using a microscope, molecules, atoms, ions and subatomic particles can be seen. That is not the case. Instead of using the term microscopic representation, this study will adopt the more contemporary term from the chemistry education literature -
particulate representation. This term does not allow for a misconception about an ability to see molecules, atoms, etc. with a microscope to form from the terminology of the representation, but rather, allows for a more accurate conception of the size of molecules, atoms, ions and subatomic particles.

The macroscopic representation is open to direct observation, for example, a balloon’s volume increasing as the pressure inside the balloon increases. The particulate representation consists of illustrations or drawings of molecules, atoms, ions and subatomic particles, adding a visual approach to understand subject matter already presented by a means of the macroscopic and symbolic representations to be explained. In the particulate representation, as well as in the ability to transition between the macroscopic, particulate and symbolic representations, a deep understanding of chemistry is present (Kozma & Russell, 1997; Gabel, 1993). The symbolic representation is where symbols, equations, formula and graphs are placed. These three representations—the macroscopic, the particulate and the symbolic—are used to describe and categorize the nature of the learning activities that occur in a classroom. For example, a chemistry teacher may use the macroscopic representation of a balloon’s volume increasing as the pressure decreases. To help students understand this phenomenon, the particulate representation may be used. For example, the teacher may show a computer simulation of gas particles moving in a closed container. The teacher then changes the pressure in the closed container within the simulation. By decreasing the pressure in the closed container, the teacher can show that the volume the gas particles occupy increases as the pressure decreases. In conclusion, the teacher may then use the symbolic representation of Boyle’s Law: $P_1V_1 = P_2V_2$
If we use the definition of PCK most scholars agree upon, that is, knowledge of representations and conceptions and preconceptions of chemistry concepts, then the content knowledge for teaching becomes very important. The discipline, such as science, will dictate the knowledge of representations and conceptions and preconceptions necessary to describing PCK. But at the same time, content even by specific scientific discipline is not enough. To speak of representations and conceptions for chemistry is to talk about too broad a topic. To be meaningful, small discrete topics within the discipline of chemistry should be discussed. For example, the representations and conceptions surrounding the gas laws can be easily managed and will provide specific insight into PCK about this specific topic in the discipline of chemistry as well as in the subject matter knowledge for teaching the gas laws.

In addressing this issue, Bell, Veal & Tippin (1998) created a hierarchy of PCK. They start with the broadest level, science PCK. For example, science PCK for science teachers is predominantly about which laboratory experiments and activities should be used in the classroom. The intermediate level of the hierarchy is discipline PCK. For example, chemistry PCK. Chemistry PCK might include knowing how and when to use specific representations of chemical phenomena, such as chemical symbols for elements or chemical reactions. The third and most specific level in Bell et al hierarchy is specific topic PCK, such as Gas Law PCK. Here specific representations, such as powerful analogies, illustrations, and examples, specific to the Gas Laws would be used to assist students in understanding the Gas Laws.

Using the Gas Laws as an example, an investigation of the literature in regard to the subject matter knowledge for teaching and pedagogical content knowledge for the Gas
Laws yielded the following.

Most chemistry courses are taught in the symbolic representation; i.e. electron configuration, chemical formula, chemical reactions, equations and graphs. A majority of teachers do use algorithmic problems, or the symbolic representation, assuming that the underlying concepts are understood (Niaz & Robinson, 1992). Little emphasis is placed on the particulate representation, the molecules, atoms, ions, electrons, etc. and what they are doing during a chemical reaction or phase change. Lin, Cheng & Lawrenz (2000) state students do not understand particulate nature of matter concepts because of an overemphasis on symbolic representations in classroom instruction. Other studies show that algorithmic skills, competence using the symbolic representation, do not necessarily yield a conceptual understanding of molecular concepts (Nakhleh 1993; Nurrenburn and Pickering 1987; Pickering 1990; Sawrey 1990). The prevalence of the symbolic representation in chemistry courses might be due to the representations presented in textbooks. De Berg (1989) study shows little emphasis is placed on qualitative understanding of the Gas Laws. That is, the macroscopic and particulate representations are not being emphasized in textbooks. The symbolic representation is being emphasized. Out of 80 exercises illustrating Boyle’s Law, only five were not symbolic in nature. It is obvious why students have difficulty understanding the macroscopic and particulate representations if 75 out of 80 exercises focus on the symbolic representation (de Berg, 1989).

The problem of students’ lack of conceptual understanding of molecular concepts is not confined to traditional classrooms. Robbins, Villagomez, Dockter, Christopher, Ortiz, Passmore, and Smith (2009) conducted a study implementing an inquiry-based
curriculum for the Gas Laws, as recommended in the National Science Education Standards. However, classroom observations, student questions, and exam results showed limited students’ understanding of the Gas Laws. Robbins et al (2009) suggested that students had difficulty with algebra, the symbolic representation, which was why the Gas Laws were not understood conceptually. Upon further investigation, results indicate that algebra’s overall role in students’ difficulties with a conceptual understanding of the Gas Laws was minimal.

Kozma & Russell (1997) speak of representational competence as the ability to navigate between the three representations to achieve a deep understanding of chemical concepts. Both Kozma & Russell (1997) and Gabel (1993) find that students are able to transfer knowledge from one representation to another only with considerable difficulty. More emphasis placed on the particulate representation can enhance students’ abilities to transfer from one representation to another (Gabel, 1993, Bodner, 2000, Kozma & Russell, 1997, Levy, 2009). However, teachers’ representational competence is unknown in the literature.

Because students have limited representational competence, they may have alternate conceptions. Much research has been done on student prior knowledge, accessing prior knowledge and student alternate conceptions for the specific content of Gas Laws (Séré and Nussbaum, 1985; Lin, Cheng & Lawrenz, 2000; Gabel & Bunce, 1994; Nakhleh, 1992). Most of the student alternate conceptions that have been identified in chemistry reveal a weak understanding of the particulate nature of matter (Nakhleh, 1992). What is interesting is that teachers have the same alternate conceptions as those held by students (Kruse & Roehrig, 2005; Lin, Cheng & Lawrenz, 2000). If teachers
hold the same alternate conceptions that their students do, those alternate conceptions become even more engrained for students and teachers. Teachers’ alternate conceptions must impact curriculum and instruction. Kruse & Roehrig (2005) postulate that teachers’ alternate conceptions may be directly transmitted to students during instruction. Further research is necessary on teachers’ alternate conceptions, as well as their representational competence, and the impact on curriculum and instruction.

In light of a lack of literature for teacher representational competence and teachers’ alternate conceptions impacting curriculum and instruction, areas of research have been suggested. Settledge (2007) suggests assembly of a concise set of alternate conceptions that all teachers should know, with a goal of using them in the development of curricular materials and teaching strategies. Another suggestion is that pedagogical content knowledge and its interplay with the teaching of specific science alternate conceptions would be productive. Additional studies have been suggested to improve topic-specific PCK through the challenging of teachers’ alternate conceptions regarding subject matter knowledge for teaching (van Driel, Verloop, & de Vos, 1998; Daehler & Shinohara, 2001; Kinach, 2001; Wilson & Wineburg, 1993).

In summary, the Gas Laws are taught in most classrooms through the symbolic representation. Yet, teachers use macroscopic demonstrations and experiments, and perhaps also graphing their experimental data, assuming that students are making connections between the representations of what is observed in the experiment and graphed data to understand the Gas Laws although, most students do not demonstrate representational transformation. The representational competence of teachers is not known. In addition, teachers seem to hold the same alternate conceptions that their
students do. However, subject matter knowledge for teaching and PCK influence one another (Daehler & Shinohara, 2001; Kinach, 2001); they are intertwined and so must by researched together. Thus, this study focuses on subject matter knowledge for teaching and PCK, specifically representations and teachers’ alternate conceptions, with respect to the Gas Laws.

Thus, the above discussion raises the following research questions:

Research question 1: With respect to the Gas Laws, what knowledge do chemistry teachers have of chemistry representations?

Research question 2: With respect to the Gas Laws, what understandings do chemistry teachers have of student alternate conceptions?

Research question 3: With respect to the Gas Laws, what is the subject matter knowledge for teaching that chemistry teachers have?
CHAPTER TWO

REVIEW OF LITERATURE

In describing chemistry content knowledge and pedagogical content knowledge, it is important to distinguish between terms as well as describing where those terms overlap. In the following, I have started with content knowledge described by Schwab (1964) and how content knowledge is different from subject matter knowledge for teaching. I then discuss pedagogical content knowledge, specifically representations and student preconceptions and alternate conceptions. Using the definitions of subject matter knowledge for teaching and representations, I present an amalgam of subject matter knowledge for teaching and representations specifically for the topics of kinetic molecular theory, Boyle’s Law and Charles’ Law.

Content Knowledge

Schwab (1964) defines content knowledge as the facts, principles, concepts and theories of the discipline, how it is organized within the discipline (substantive structures) and what counts as evidence and proof in the discipline (syntactic structures). Thus, content knowledge includes not only the facts of a field, but also the organization and relationships of those facts as well as how new information, or facts, concepts or principles, are treated in the field. A good example is the behavior of gases in chemistry. There are five major laws that predict the motion and behavior of gases: Boyle’s, Charles’, the Ideal Gas, the Combined Gas, and Avogadro’s Law. Each law describes a specific relationship between two or more of fundamental properties of gases, mass, volume, temperature and pressure. These relationships are typically presented algebraically and graphically. These are the laws of the discipline.
Schwab also mentions the theories of the discipline as part of content knowledge. For the example of the behavior of gases, the theory is the kinetic molecular theory. In this theory, matter is described as small particles that behave in specific and predictable fashion. For example, gas particles are uniformly distributed in a closed system, are in constant motion, heating and cooling cause changes in particle motion, liquifaction is viewed as a change in particle density and there is empty space between the particles of a gas. This is the theory that is behind the five laws of gas behavior mentioned above.

These facts, theories, and how they are organized are substantive structures. In addition, when new facts, concepts or principles are proposed to the discipline of chemistry regarding the behavior of gases, the manner in which the community of scholars within the discipline treats those new ideas constitute the syntactic structures. Thus, content knowledge will be defined as the facts, theories, concepts, and principles of a discipline, its substantive structures and its syntactic structures.

Subject Matter Knowledge for Teaching

While Schwab defines content knowledge for the discipline of science, we cannot safely assume that this definition accurately describes the content knowledge used by teachers in high school classrooms. Teachers possess a specialized form of content knowledge for the classroom that is based on the academic discipline but is uniquely different (Deng, 2005). High school chemistry teachers typically have a degree in chemistry and have experienced the discipline of chemistry as students in college. Yet, the content knowledge chemistry teachers use to teach in their high school classrooms may be different from that found in a more advanced academic setting.
For example, while there are five laws that govern the behavior of gases, a high school chemistry teacher may teach only one of the laws for various reasons, such as time in the school year, abilities of the students, and limited requirements of the district or state standards. For example, the behavior of gases using the kinetic molecular theory and the Ideal Gas Law can eventually be used to understand the molecular attraction of gases as measured by the van der Waals equation for gases that have higher pressure and temperatures than the Ideal Gas Law allows for. However, it is not appropriate in relating the Ideal Gas Law to molecular attraction using an equation for gases that only works at extreme pressure and temperatures in a ninth grade physical science classroom. While the teacher may know this information, it is not necessary or appropriate for the teacher to teach this information to his or her students.

Here we can see that the content knowledge taught in the classroom is different from that of the academic discipline. Teachers not only possess the substantive and syntactic structures of the discipline of science, they also possess the knowledge of what are the appropriate substantive and syntactic structures for teaching chemistry in a specific classroom. Let us then define this form of content knowledge, that is, the content knowledge taught in the classroom plus its related substantive structures and syntactic structures, as “subject matter knowledge for teaching.”

*Pedagogical Content Knowledge*

Subject matter knowledge for teaching is transformed from something the teacher knows into something that students can work with in the classroom. This transformation of subject matter knowledge for teaching involves the use of pedagogical knowledge—instructional practices, educational aims, knowledge of the learning process, knowledge
of learners and classroom management skills, as well as knowledge of the broader context—the teacher’s knowledge of his or her students, school and community. This mixture or amalgam of content knowledge, pedagogical knowledge and context knowledge has been gathered and summarized under the concept “pedagogical content knowledge” (PCK) (Shulman, 1986; Grossman, 1990; Gess-Newsome, 1999). Thus, subject matter knowledge for teaching is transformed by PCK into lesson plans so that students can work with the content knowledge (Abell, 2007).

The Gas Laws can provide an example. A teacher understands the gas laws, the substantive and syntactic structures of the gas laws. The subject matter knowledge for teaching employed in teaching the gas laws also require the teacher to know, understand, and evaluate pedagogy, his or her students’ conceptions, and what representations that can be presented so that students can learn the gas laws. It is the teacher’s PCK that allows the subject matter knowledge for teaching to be transformed into activities that students can engage with in the classroom to learn the gas laws.

Since the naming of pedagogical content knowledge (PCK) by Lee Shulman in 1986, much of the last twenty years has been devoted to defining PCK and determining ways in which to measure it. There are many definitions of PCK; some definitions are built upon Shulman’s (Grossman, 1990; Magnusson, Krajcik and Borko, 1999; Van Driel, Verloop & de Vos, 1998) and others are completely different, requiring a new name due to more emphasis on one domain of PCK, such as pedagogical context knowledge (Barnett & Hodson, 2001). However, most scholars agree that PCK includes the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a
word, the ways of representing and formulating the subject that make it 
comprehensible to others and includes an understanding of what makes the 
learning of specific topics easy or difficult; the conceptions and 
preconceptions that students of different ages and backgrounds bring with 
them to the learning of those most frequently taught topics and lessons. 
(Shulman, 1986, p.9-10).

It is this definition of PCK that will be used throughout this stu-
dy—PCK is 
representations of the subject and the conceptions and preconceptions that students have 
of the subject.

Representations

Bruner (1966) wrote of three representations as humans experience cognitive 
growth or thinking. At first, when humans are infants and just beginning to make sense 
of the world, infants define their world, or think, based on the enactive representation. 
The enactive representation is action-based. Actions performed on objects act as 
definitions for those objects. For example, an infant may be given a rattle to play with. 
The infant instinctively shakes the rattle. However, once the rattle is removed from the 
infant’s grasp, the infant will continue a shaking motion to return the rattle to her grasp 
(Bruner, 1966). In the enactive representation, the manipulation of objects by action 
defines those objects. Or, thinking or cognitive growth is based in manipulation of 
objects. The enactive representation is the most rudimentary of the three representations 
he presents.

The second stage of cognitive growth is the iconic representation (Bruner, 1966). 
In this stage, infants to toddlers are able to understand the world through images or
spatial understandings that does not require an action. In addition to the manipulation of objects, thinking can be done using pictures and images. For example, a child can understand the idea of “triangle” by initially tracing the triangle shape with her finger, an enactive representation (Bruner, 1966). However, over time, tracing will no longer be required and the child can “recognize” the image or shape of a triangle. Recognizing a triangle through a shape or image is using the iconic representation.

The final stage of cognitive growth is the symbolic representation. The symbolic representation is the representation of letters, numbers, and abstract codes, such as language (Bruner, 1966). It is the symbolic representation, or language, which becomes the preferred representation to understanding the world. Verbal and written communication is emphasized in society. Because such emphasis is placed on thinking in the symbolic representation, thinking through action, as in the enactive representation, or through imagery, as in the iconic representation, tend to decay (Bruner, 1966). However, without the cognitive growth of the enactive and iconic representations, the cognitive growth of the symbolic representation may not develop fully.

Johnstone (1991) wrote about representations within the discipline of chemistry. He identified three representations specific to the discipline and the teaching of chemistry—macroscopic, particulate and symbolic. He describes the macroscopic representations as the realm of what can be seen in the normal context of daily life, such as a balloon inflating as air is blown into it. The particulate representation reflects the particulate nature of matter. Here, focus is on the molecules, atoms and ions, and their behavior. For example, a computer animation that shows solid spheres moving and colliding in a closed container at a specific temperature and pressure. The symbolic
representation focuses on the symbols, equations and graphs that can be used to show relationships between variables. For example, Boyle’s Law of $P_1 V_1 = P_2 V_2$ is a symbolic representation.

Bruner (1966) and Johnstone’s (1991) representations appear similar even though Bruner is discussing cognitive growth of humans and Johnstone is discussing chemistry classrooms. Bruner’s enactive representation is based on actions, manipulation of objects. Understanding and thinking comes through acting. This representation is the most direct representation. Johnstone’s macroscopic representation of what can be observed in daily life, such as a balloon inflating when air is blown into it, is similar to Bruner’s manipulation of objects. An action, blowing air into a balloon, describes the balloon—it inflates. The enactive representation, Bruner’s representation, is seeing and acting. The macroscopic representation, Johnstone’s representation, is acting and seeing. The enactive representation can be argued as equivalent to the macroscopic representation.

An argument of equivalence can be made for Bruner’s (1966) iconic representation and Johnstone’s (1991) particulate representation. An image or picture represents a real-world object. For example, the image of a triangle drawn on a piece of paper represents a triangular object. In chemistry, Johnstone’s particulate representation of drawings of molecules in a liquid is an image that represents a larger macroscopic object, such as water in a glass. For Bruner, the iconic representation, an image of a triangle, is a model of an action/object, the tracing of a triangle shaped block, in the enactive representation. For Johnstone, the particulate representation, drawing of
molecules, is a model for the larger object, the glass of water, in the macroscopic representation.

Bruner’s symbolic representation utilizes letters, numbers and abstract codes such as language to understand the world. Johnstone’s symbolic representation uses letters, numbers, and abstract codes, such as chemical equations, to understand the world of chemistry. Both Bruner and Johnstone’s symbolic representations require a sophisticated understanding of the other two representations, the enactive/macroscopic representations and the iconic/microscopic representations, to make sense of the world and chemistry.

Gabel (1993, 1998) extended the discussion of Johnstone’s three representations of chemistry. Most chemistry courses are taught in the symbolic representation; i.e. electron configuration, chemical formula, chemical reactions, equations and graphs. Little emphasis is placed on the particulate representation, the molecules, atoms, ions, electrons, etc. and what they are doing during a chemical reaction or phase change. Yet, chemistry teachers expect their students to transition between the macroscopic, particulate and symbolic representations with ease. Kozma & Russell (1997) speak of representational competence as the ability to navigate between the three representations to achieve a deep understanding of chemical concepts. Both Kozma & Russell (1997) and Gabel (1993) find that students are able to transfer knowledge from one representation to another only with considerable difficulty. More emphasis placed on the particulate representation will enhance students’ abilities to transfer from one representation to another (Gabel, 1993, Bodner, 2000, Kozma & Russell, 1997, Levy, 2009).
The three representations of macroscopic, particulate and symbolic do describe chemistry; but there is an alternate conception inherent in the representations. The symbolic representation includes mathematical formulas, symbols, equations and graphs. Symbols such as Na for the element sodium or $P_1V_1 = P_2V_2$ where P is pressure and V is volume seem appropriately placed in the symbolic representation. Symbols, such as Na, P and V are used to express larger concepts such as elements and variables of an equation. However, graphs, while symbolic, seem to require a more complex type of mental process to understand than the relatively simple relationship of Na for sodium and P for pressure. To read and understand a graph, one is required to access a larger domain of knowledge and thought processes in order to understand the relationship being expressed by the graph. The ability to read and understand a graph seems to require its own form of representation. Thus, I propose that there should be four representations: the macroscopic, that of which we can see, the particulate, that of which includes molecules, atoms and ions, the symbolic, that of which include symbols, formulas and equations, and that of graphic, that of reading and understanding graphs.

**Preconceptions and Alternate Conceptions**

Recall the definition of PCK that will be used throughout this study—PCK is representations of the subject and the conceptions and preconceptions that students have of the subject. Representations were discussed in the previous section. Here, discussion of student preconceptions, or prior knowledge, and alternate conceptions is presented.

Much research has been done on student prior knowledge, accessing prior knowledge and student alternate conceptions for the specific content of gas laws (Séré and Nussbaum, 1985; Lin, Cheng & Lawrenz, 2000; Gabel & Bunce, 1994; Nakhleh,
In Children’s Ideas of Science, Séré and Nussbaum documented numerous preconceptions and alternate conceptions about the particulate nature of matter—in other words, what the particles of a gas look like and how those particles behave. A number of assessments have been developed to assess students’ preconceptions and alternate conceptions (Robinson & Nurrenbern, accessed April 2009; Novich & Nussbaum, 1981; Noh, 1991) about the particulate representation.

Most of the student alternate conceptions that have been identified in chemistry reveal a weak understanding of the currently accepted model of matter (Nakhleh, 1992), the particulate nature of matter. This model states that matter is made of discrete particles that are in constant motion and have empty space between them (Novich & Nussbaum, 1981). In order to understand the Gas Laws, the particulate nature of matter and the kinetic molecular theory must also be understood. Students see a static, rather than kinetic, conception of the particulate model of matter. For most students, matter is a continuous medium that is static and space filling (Séré & Nussbaum, 1985; Nakhleh, 1992).

Yet, current research on alternate conceptions seems to have faded away (Settledge, 2007). In response to this statement, Settledge sent out emails to a few veteran science teacher educator colleagues on the state of misconception research. He received a number of replies, which he categorized. In a summary of “areas recommended for further study”, Settledge cites a number of respondents. For example, one respondent’s advice was to produce a concise set of alternate conceptions that all teachers should know, with a goal of using them in the development of curricular materials and teaching strategies. Another informant suggested that pedagogical content knowledge and its
interplay with the teaching of specific science alternate conceptions would be productive. It seems that veteran science teacher educators want to marry misconception research with pedagogical content knowledge yet have not done so at this time. The future of misconception research seems to be tied to pedagogical content knowledge. As research on PCK has been done, misconceptions, or alternate conceptions teachers have, comes to the fore (Van Driel, Verloop & de Vos, 1998; Daehler & Shinohara, 2001; Kinach, 2001). Further discussion of teachers’ alternate conceptions will be presented in this chapter.

If we use the definition of PCK most scholars agree upon, that is, knowledge of representations and conceptions and preconceptions of chemistry concepts, then the content knowledge becomes very important. Geddis (1993) pointed out that there are content-specific pedagogical skills, such as how to teach electricity or how to teach the gas laws. Bell, Veal, & Tippins (1998) postulated three hierarchical types of PCK. Science PCK is the broadest type, such as PCK for use of models, laboratory equipment, and inquiry based teaching. The second type is specific discipline PCK, such as PCK for teaching physics. The third type, and most particular, is specific topics PCK, such as PCK for teaching the gas laws. Bell et al. suggest that PCK is not only specific for broad disciplines, such as physical science versus history or sociology, but also specific for discrete topics within a particular field of science. Thus, PCK for the gas laws would be different from PCK for chemical reactions, which would be different from PCK for atomic structure. The specific academic topic becomes crucial to discussing PCK.

The content area will dictate the knowledge of representations and conceptions and preconceptions necessary to describing PCK. But, content area is also not enough.
To speak of representations and conceptions for chemistry is to talk about too broad a topic. To be meaningful, small discrete topics within the discipline of chemistry should be discussed. For example, the representations and conceptions surrounding the gas laws can be easily managed and will provide specific insight into PCK about the specific topic in the discipline of chemistry as well as in the subject matter knowledge for teaching the gas laws.

Content Knowledge for the Behavior of Gases

In order to understand the PCK for the behavior of gases and the preconceptions and alternate conceptions that students bring to the learning of the behavior of gases, it is important to know the content knowledge for the behavior of gases. Due to the complexity and size of the entire topic of the gas laws, this study will focus on the Kinetic Molecular Theory, Boyle’s Law, and Charles’ Law. What follows is a summation of the kinetic molecular theory, upon which the gas laws are built, Boyle’s Law and Charles’ Laws. Further discussion as to the selection of these topics follows in chapter three.

Kinetic Molecular Theory

The behavior of gases is built upon the substantive structure of the kinetic molecular theory. Kinetic Molecular theory of gases (Zumdahl, 2002) is a theoretical model constructed to account for ideal gas behavior. This model assumes:

1. that the volume of the gas particles is zero,
2. there are no interactions between particles, and the
3. particles are in constant motion, colliding with the container walls to produce pressure.
4. In addition this model shows that the average kinetic energy of the gas particles is directly proportional to the Kelvin temperature of the gas. (Zumdahl, 2002). Most gas law instruction is of the symbolic representation, focusing on the gas laws as equations and formulas (de Berg, 1989). However, in order to conceptually understand the nature of the gas laws, the kinetic molecular theory must be understood as well.

**Boyle’s Law**

Based on the substantive structure of the kinetic molecular theory, the gas laws can be used to describe the behavior of gases. Boyle’s Law is one such example. Boyle’s Law states that the volume of a given sample of gas at constant temperature varies inversely with the pressure (Zumdahl, 2002). In other words, \( P_1V_1 = P_2V_2 \) where \( P \) is pressure and \( V \) is volume. The equation can be understood from a purely symbolic perspective. Yet, students have difficulty transferring from the symbolic representation to the particulate representation (Keig & Rubba, 1993; Kozma & Russell, 1997). For example, students will be able to use the formula to calculate a fourth variable of \( P_1V_1 = P_2V_2 \) when given the other three variables. However, students will not be able to describe what is happening to the gas particles when one of the four variables of \( P_1V_1 = P_2V_2 \) changes. For example, students will not be able to say that when volume increases, the gas particles hitting any section of the wall in a given time decreases and the pressure decreases.

**Charles’ Law**

Charles’ Law is another substantive structure of the behavior of gases. Charles’ Law states that the volume of a given sample of gas at constant pressure is directly proportional to the temperature in degrees Kelvin (Zumdahl, 2002). In other words,
\[ \frac{V_1}{V_2} = \frac{T_1}{T_2} \] when pressure is constant. Again, students have difficulty transferring from the symbolic representation of the equation to the particulate representation where the kinetic molecular theory is so powerful. Students will not be able to explain that at a higher temperature, gas particles move faster, striking each other and the walls of their container more frequently and with greater force. For the pressure to stay constant, volume must increase so that the particles have farther to travel before striking the walls. Having to travel farther decreases the frequency with which the particles strike the walls of the container. (Dingrando et al, 2002).

**Pedagogical Content Knowledge for Gases**

The teaching of the Gas Laws focuses primarily on the symbolic representation (Gabel, 1993; Bodner & Domin, 2000; de Berg, 1989). Deep understanding of the Gas Laws requires the understanding and ability to transition between the macroscopic, particulate, symbolic, and graphic representations (Kozma & Russell, 1997; Gabel, 1993). However, in order to understand the behavior and properties of gases, the kinetic molecular theory must be understood. This theory puts forth an explanation of the properties and behavior of gas molecules. There are two issues with PCK and the Gas Laws. First, teachers hold many of the same alternate conceptions about the particulate nature of matter, as do their students (Lin, Cheng, & Lawrenz, 2000; Kruse & Roehrig, 2005). In addition, the particulate representation of the kinetic molecular theory is not emphasized in college classrooms (Bodner & Domin, 2000). Thus, teachers may not be familiar with the particulate representation or have the ability to transition between the macroscopic and symbolic representations so prevalent in classrooms (Gabel, 1993) and the particulate representation. Since PCK is what transforms the subject matter
knowledge for teaching into lesson plans and activities designed for student learning of
the Gas Laws, any deficiency in PCK, such as those mentioned above, will impact the
transformation and may be apparent in curriculum and instruction of the Gas Laws.

Subject Matter Knowledge for Teaching and Pedagogical Content Knowledge for Gases

In keeping with Settledge (2007) and Bell et al. (1998), a marriage of subject
matter knowledge for teaching and PCK, specifically the representations, for the behavior
of gases, eight textbooks commonly available for purchase in school districts were
analyzed. The following Gas Laws PCK Model is a result (Table 1). The top row
displays the four representations used in chemistry are displayed. The representations are
macroscopic, the level that has observable processes; the particulate, the level that
explains the arrangement and behavior of molecules, atoms, ions and subatomic particles;
the symbolic, where symbols, formulas, and equations take their place; and the graphic,
where graphs of the relationships of variables can be seen.

Table 1: —The Gas Laws PCK Model

<table>
<thead>
<tr>
<th>Representations</th>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Molecular Theory</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boyle’s Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charles’ Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gay-Lussac’s Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avogadro’s Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined Gas Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Down the first column, the specific subject matter knowledge for teaching that commonly occurred in the eight textbooks. The gas laws are made up of five laws which, when joined together, culminate in the Ideal Gas Law. In order to understand any of the gas laws on a conceptual level, knowledge of the kinetic molecular theory (KM theory) is essential as well as the ability to identify a closed or open system.

Not all of the textbooks included all of the subject matter knowledge for teaching topics or all four of the representations shown in the Gas Laws PCK Model. However, all subject matter knowledge for teaching topics and representations were included for a complete model. The grey boxes represent blanks in the literature (de Berg, 1989; textbooks examined) and the inability of some subject matter knowledge for teaching topics to be represented by specific representations. For example, none of the textbooks included symbolic or graphic representations for the kinetic molecular theory. The kinetic molecular theory cannot be represented with a symbolic or graphic representation. Thus the intersection of kinetic molecular theory and symbolic and graphic representations were left blank.

The Gas Laws PCK Model developed for this study includes more than the information displayed in Table 1. The intersection of specific subject matter knowledge for teaching and representations was documented for each subject matter knowledge for teaching topic. Using Boyle’s Law as an example, we can see the intersection of the
four representations and the subject matter knowledge for teaching might be the following (Table 2).

*Table 2: Subject Matter Knowledge for Teaching and the Four Representations for Boyle’s Law*

<table>
<thead>
<tr>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syringe/book lab</td>
<td>When volume increases, the gas particles hitting any section of the wall in a given time decreases and the pressure decreases.</td>
<td>( V = \text{constant} \times \frac{1}{P} ) OR ( PV = \text{constant} ) OR ( P_1 V_1 = P_2 V_2 )</td>
<td></td>
</tr>
</tbody>
</table>

In the macroscopic representation, a typical experiment uses a syringe and textbooks to illustrate what happens to volume as pressure increases. In order to understand the experiment, the particulate representation can be used to explain what is happening on a particulate level. For example, when volume decreases, the gas particles hitting any section of the wall in a given time increases and the pressure increases. The symbolic representation illustrates Boyle’s law based on the variables of pressure and volume while the graphic representation shows a graph of the same variables as in the
symbolic representation. By using the Gas Laws PCK Model it may be possible to determine what subject matter knowledge for teaching teachers are using and which representations they use to convey that knowledge in the classroom.

PCK is obtained through experience that is an integration of skills used in a classroom, is topic specific such as the gas laws instead of chemistry as a whole and somehow is more than just subject matter. For example: Which demonstration of the many that exist will illustrate Boyle’s Law the best for a specific group of students while challenging student alternate conceptions and addressing multiple representations? The outside observer only sees the demonstration chosen and does not know about the other demonstrations or the reasons behind the selection. In order to evaluate or assess PCK, a teacher must be asked about his or her curriculum and instruction for specific topics. Specifically, what are the most powerful analogies, illustrations, examples, explanations, and demonstrations for representing and formulating the subject that make it comprehensible to students and includes an understanding of what makes the learning of specific topics easy or difficult and what preconceptions and alternate conceptions do students bring to the learning of a subject? This study will describe the knowledge chemistry teachers have of chemistry representations, student conceptions and the subject matter knowledge for teaching have regarding the behavior and properties of gases.
CHAPTER THREE
RESEARCH METHODS

Research Design

The purpose of this study is to investigate teachers’ PCK, particularly with regard to their teaching of the Gas Laws. While PCK is a dynamic construct, it was determined that this study would focus on specific aspects of PCK, that is, teachers’ subject matter knowledge for teaching, the representations they used in the teaching of the Gas Laws, and teachers’ understandings of student prior knowledge and alternate conceptions of the Gas Laws.

This study is about describing teachers’ PCK and subject matter knowledge for teaching. Thus, the design of this research project is a descriptive multiple case study or descriptive collective case study (Merriam, 1998; Creswell, 1998). Each participant is an individual case, but all of the participants are bound together as a multiple case study. This study is bounded by time and context, as the participants are high school chemistry teachers who taught a unit on Gas Laws, during the 2008-2009 school year.

The characterization of the multiple case study as descriptive (Merriam, 1998) suggests just that. This study intends to provide thick, rich descriptions (Merriam, 1998) of within-case as well as cross-case PCK and subject matter knowledge for teaching. A descriptive multiple case study was chosen because case study as a methodology can “Illustrate the complexities of a situation—the fact that not one but many factors contributed to it…include vivid material—quotations, interviews…obtain information from a wide variety of sources” (Olson, in Creswell, 1998, pp. 30-31).
The thick, rich descriptions will come from multiple sources of information (Creswell, 1998). During the course of the study, multiple sources of information were gathered (Creswell, 1998). While Yin (1989) recommends six types of information: documentation, archival records, interviews, direct observations, participant observations and physical artifacts, it was not possible within the scope of this study for direct observations of the participants in their classrooms or for participant observations. In this study, four of the six types of information, documentation through direct assessment, archival records, interviews and physical artifacts were collected. The participants supplied these data through a written assessment, two interviews, and classroom artifacts used in their work.

Participant Selection

In order to permit adequate assessment of chemistry teachers’ PCK in regard to the Gas Laws, the participants would have to have common characteristics that allowed for comparison of PCK and subject matter knowledge for teaching. Criterion-based selection of the participants was employed (Merriam, 1998). Participants were selected based on the following criteria: they must hold a Bachelor of Science degree in Chemistry, have taught any level of chemistry in a high school setting for three or more years, and must also have taught a unit on the Gas Laws during the 2008-2009 school year. These specifications allowed for the assumptions that each participant would have experience in the classroom that would result in the development of PCK and subject matter knowledge for teaching the Gas Laws (Abell, 2007; Grossman, 1990; Gess-Newsome, 1999).
Initially, snowball sampling (Merriam, 1998) based on participant criteria took place. The researcher and her adviser’s professional contacts in the metropolitan area in the Midwest were used to identify potential participants. Potential participants were asked to suggest other potential participants. Ideally, four participants were needed for this research study. Initially, thirteen chemistry teachers were contacted by email for recruitment. Eight teachers responded. Two respondents failed to qualify because they do not have a Bachelor of Science degree in chemistry; two more, though qualified, could not participate in the study due to scheduling conflicts. Of the four remaining teachers who responded to the recruitment email, all met the selection criteria and agreed to complete the written assessment, interviews, and collection of artifacts.

Once the participant selection had taken place, comparison of the four participants was done to determine the nature of the sample. Table 3.1 illustrates multiple nodes at which the four participants were compared.

Table 3.1: Comparison of Four Participants Backgrounds and Schools

<table>
<thead>
<tr>
<th></th>
<th>Erik</th>
<th>Julien</th>
<th>Matthew</th>
<th>Sam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree(s)</td>
<td>B.S. Chemistry</td>
<td>B.S. Chemistry</td>
<td>B.S. Chemistry</td>
<td>B.S. Chemistry</td>
</tr>
<tr>
<td></td>
<td>M.Ed.</td>
<td>M.Ed.</td>
<td>M.Ed.</td>
<td>M.S. Biochemistry</td>
</tr>
<tr>
<td>Licensure Years Exp.</td>
<td>U of M 3</td>
<td>U of M 8</td>
<td>U of M 4</td>
<td>Unknown 40</td>
</tr>
<tr>
<td>Courses Taught</td>
<td>Many</td>
<td>Chemistry and</td>
<td>Chemistry &amp; 9th gr. Physical Science</td>
<td>Chemistry and Advanced</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Honors Chemistry Urban</td>
<td>Suburban</td>
<td>Chemistry</td>
</tr>
<tr>
<td>School-Urban, Suburb</td>
<td>Suburban</td>
<td>Suburban</td>
<td>Suburban</td>
<td>Rural</td>
</tr>
<tr>
<td>Class Size</td>
<td>30-36</td>
<td>17-27</td>
<td>22-24</td>
<td>15-18</td>
</tr>
<tr>
<td>Diversity</td>
<td>Not diverse</td>
<td>Very diverse</td>
<td>Not diverse</td>
<td>Diverse</td>
</tr>
<tr>
<td>Public/Private</td>
<td>Public</td>
<td>Private-Roman Catholic</td>
<td>Private</td>
<td>Private-Roman Catholic</td>
</tr>
<tr>
<td>Block/Regular</td>
<td>Block &amp; Regular</td>
<td>Regular</td>
<td>Regular</td>
<td>Block &amp; Regular</td>
</tr>
<tr>
<td>Elective or Required</td>
<td>Elective</td>
<td>Elective</td>
<td>Elective</td>
<td>Elective</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>Grade</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Years of science required</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Since only four participants met the criteria for the study and were willing to complete all data collection, this sample became a convenient sample (Merriam, 1998). However, while convenience may have been a factor in participant selection at the time of the first data collection, comparison of the four participants shows similarities based on the sample selection criteria, licensure, school schedule, and grade level taught, as well as, variation based on diversity of students taught, type of school, school location and class size.

Protection of Human Subjects

Informed consent was obtained in writing from all participants. All participants were informed of the risks and benefits of participation in the study. Participants could at any time chose to leave the study and have any data collected returned or not used in the analysis. Data was kept in a locked file cabinet and on a computer that was password protected. Only the researcher and the researcher’s advisor had access to the data. No participant expressed interest in viewing the analysis or final work. Thus, the participants did not read their cases.

Data Collection

Data collection based on the Gas Laws PCK Model (see Table 3.2) consisted of four primary sources: a written assessment of Gas Law content knowledge, a first interview based upon the assessment of subject matter knowledge for teaching, a semi-structured second interview inquiring into participants’ actual practices and methods in
Table 3.2: The Gas Laws PCK Model

<table>
<thead>
<tr>
<th>Representations</th>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>KM Theory</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boyle’s Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charles’ Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gay-Lussac’s Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avogadro’s Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined Gas Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ideal Gas Law</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closed v. Open System</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The grey shaded areas represent an intersection of subject matter knowledge for teaching and representations that does not make sense. It is impossible to describe the kinetic molecular theory in a symbolic or graphic representation.
teaching the Gas Laws, and collection of classroom artifacts. These four primary sources were used to determine the participants’ subject matter knowledge for teaching and to identify both the representations used by participants and the understandings they have of student conceptions in teaching the Gas Laws (see Table 3.3).

Table 3.3: Alignment of Research Questions and Data Sources

| Research Q1: What knowledge do chemistry teachers have of chemistry representations with respect to the behaviors and properties of gases? | Secondary Source | Primary Source | Primary Source |
| Research Q2: What understandings do chemistry teachers have of student conceptions with respect to the behaviors and properties of gases? | Primary Source | Secondary Source |
| Research Q3: What is the subject matter knowledge for teaching that chemistry teachers have regarding the behaviors and properties of gases? | Primary Source | Secondary Source |

*Design of the Subject Matter Knowledge for Teaching Assessment*

Lin et al (2000) designed four chemistry scenarios that focused on the macroscopic and particulate representations of Boyle’s Law, Charles’ Law and the kinetic molecular theory. However, two of the scenarios included additional chemistry
topics besides the Gas Laws. In order to assess the participants’ subject matter knowledge for teaching regarding the Gas Laws, the scenarios placed before them should focus solely on the Gas Laws. Thus, two questions were replaced with one different scenario that focused solely on Boyle’s Law.

As stated above, Lin et al focused on the macroscopic and particulate representations, with no questions related to the symbolic or graphic representations. To address the symbolic and graphic representations of Boyle’s and Charles’ Laws, additional questions were added to the assessment for these two scenarios. This assessment was used to determine the extent of participants’ subject matter knowledge for teaching, that is, to illuminate their conceptual understanding of the Gas Laws in each of the four representations (Lin, Cheng, & Lawrenz, 2000). Thus, the subject matter knowledge for teaching assessment consisted of one question focusing on the kinetic molecular theory and the particulate representation, one question focusing on Boyle’s Law using all four representations, and one question focusing on Charles’ Law using all four representations (see Figure 3.1 below or Appendix B).

Pilot Study

A pilot study of the first interview protocol and the subject matter knowledge for teaching assessment was conducted in May of 2009, consisting of interviews of two pilot study participants. The first of these participants is an acquaintance of the researcher’s advisor; there was not, however, any previous contact between the researcher and this pilot study participant. The pilot study participant, a native of Kenya where he was a chemistry teacher, is at the present time a graduate student at the University of
1. The Erlenmeyer flask in the diagram below was evacuated and filled with equal amounts of oxygen and carbon dioxide at room temperature. The flask was then stoppered. Describe and/or draw the motion of the particles in the flask. Explain your reasoning.

b. If a burner is put under the flask and kept burning for a few seconds, describe and/or draw the motion of particles in the flask? Explain your reasoning.
2a. Using the diagram below, predict what will happen to the level of oil in the glass tube as air is added from the pump in the right of the diagram.

b. Using words and/or drawings, explain what is happening to the air particles in the reservoir and the glass tube before and after the air is added.

c. What data would you collect to know where the volume of trapped air in the glass tube would be for any given pressure?

d. How would you collect that data?

e. What would you plot if you were to graph the data?
3. An Erlenmeyer flask is closed with a stopper connected to a glass tube. A drop of oil, as shown in Figure 3, seals the glass tube. We move the whole apparatus in the diagram from a room with a temperature of 26°C (299 K) to an outdoor yard with a temperature of 5°C (278 K).

a. Predict what direction the oil plug will move or if it will remain motionless?

b. Explain your prediction using words and/or drawings.

c. What data would you collect to know where the oil drop would be when the apparatus is in a room at 120°C (393 K)?

d. How would you collect that data?

e. What would you plot if you were to graph the data?
Minnesota. His teaching experience is five years’ teaching the British curriculum that has been adopted by Kenya.

The second person interviewed for the pilot study is a chemistry teacher employed by the same high school that presently employs the researcher. This participant has been teaching chemistry for six years at the same school and has taught the Gas Laws during each of the six years.

The results of the pilot study confirmed the reliability and trustworthiness (Lincoln and Guba, 1985) of the interview protocol and subject matter knowledge for teaching assessment.

Data Collection 1

The first data collection consisted of an assessment of subject matter knowledge for teaching, conducted orally (see Appendix B), and a first interview (see Appendix C). In the initial interview of the first participant, the subject matter knowledge for teaching assessment was conducted first and was followed by the first interview questions. During this initial interview, it became apparent to the researcher that the interview was disjointed and that the first participant’s responses were not fluid. Ideas were started and stopped for each scenario and then picked up again when the scenarios were re-visited towards the end of the interview. While the researcher thinks these data collected from the first participant are trustworthy, a change in interview protocol was enacted. The remaining three interviews were conducted in such a manner that the first interview questions were interspersed with the subject matter knowledge for teaching assessment; consequently, participants’ responses were fluid and flowed continuously.
To begin, participants were asked to answer the questions in the subject matter knowledge for teaching assessment aloud and were encouraged to draw or write as they answered the questions. The assessment focused on the macroscopic, particulate, symbolic and graphic representations of the Gas Laws.

In addition to answering the assessment questions aloud (see Appendix C), the first interview was structured primarily to discover participants’ thought processes used in responding to the assessment questions, and thereby provided insight into the depths of their subject matter knowledge for teaching regarding the Gas Laws. Participants were asked to explain why they answered each question as they did so that their responses were clear. The participants’ responses addressed the third of our three research questions posed in Chapter 1 of the present study.

A secondary though important objective of this first interview, added in the interest of efficient time management, was to begin to illuminate participants’ pedagogical content knowledge of the Gas Laws. Although pedagogical content knowledge was the primary concern of the second interview, it was approached here in two ways. The first attempt at exposing participants’ PCK was to ask them about the possible use in their own classrooms of the apparatus presented in the second and third scenarios of the subject matter knowledge for teaching assessment. The second attempt at exposing PCK was in the context of teacher-student conversation in the classroom setting, particularly as it applies to student conceptions.

The first attempt to uncover participants’ PCK was through direct questioning of the use of the apparatus presented in the second and third scenarios of the assessment (see Appendix B for the apparatus and Appendix C for the interview questions). By asking
about the use of the apparatus in their classrooms, participants were presented with novel situations and asked if they would use the apparatus, how they would use it and what their objectives would be for students if they used the apparatus. Participants’ PCK, particularly the representations, could be seen as participants described how they and their students would use and benefit from the apparatus. This portion of the first interview relates to the first of the three research questions posed in Chapter One of this study.

In the second attempt at exposing participants’ PCK, participants were presented with novel scenarios of the Gas Laws (Nussbaum, 1985; Chemical Concept Inventory) and asked to provide common student alternate conceptions seen in their classrooms (see Figure 3.2 below or Appendix C). After student alternate conceptions were obtained, participants were then asked to talk through the manner in which they would address these alternate conceptions in their classroom. This portion of the first interview relates to the second of our three research questions posed in Chapter One of the present study.

Data Collection II

The second interview (see Appendix F) and collection of artifacts were used to determine the principle representations used by participants when teaching the Gas Laws, and thereby shed light on participants’ pedagogical content knowledge. The Gas Law subject matter knowledge for teaching and the representations were mapped on the Gas Laws PCK Model (see Table 3.2). The second interview was designed to allow the participant to walk the interviewer through their unit on the Gas Laws. It was envisioned that as the participant describes how he or she teaches the Gas Laws, the participant would provide
Figure 3.2: Student Conceptions Questions from Subject Matter Knowledge for Teaching Assessment

5. The Tasks shown below were given to a number of students.

A. Here is a closed flask containing air.

B. The flask is connected to an evacuating pump, and some of the air in the flask has been pumped out of it.

C. Here is the closed flask after some of the air has been pumped out.

Read the story in drawings A, B and C above. As you may know, a gas is often pictured as composed of particles. In drawings, particles are usually pictured as tiny dots.

Task 1. Using dots, make a picture of the air in the flask in drawing A (above left), as it was before the pump was connected and used.

Task 2. Using dots, make a picture of the air remaining in the flask in drawing C (above, right) as it is after some air was removed by using the pump.

In the flask to the left, draw what you think your students will draw for drawing C (as it is after some air was removed by using the pump)?

How would you address this in your teaching?
artifacts of lectures, experiments, demonstrations, worksheets, etc. to illustrate which representations are presented to students. For example, a participant provided the interviewer with a worksheet, which requires students to use Boyle’s Law to calculate different pressures or volumes; this worksheet shows that the teacher uses the symbolic representation for this assignment. This representation for Boyle’s Law would be mapped upon the Model (see Table 3.2) at the intersection of Boyle’s Law and symbolic representations.

The second interview was also designed to determine if the participants consider student prior knowledge and alternate conceptions, and how those are addressed in teaching the Gas Laws. Participants’ consideration of student prior knowledge and
alternate conceptions when teaching the Gas Laws was determined by direct questioning during the interview.

It is possible that during the second interview participants’ subject matter knowledge for teaching was illuminated. Any subject matter knowledge for teaching revealed at this time was used as secondary data for the subject matter knowledge for teaching assessment and first interview, which focused on determining participants’ subject matter knowledge for teaching regarding the Gas Laws. Thus, the second interview responded to the first and second of our research questions posed in Chapter One of the present study, with the possible addition of information relating to the third research question.

The subject matter knowledge for teaching assessments and artifacts were collected and scanned into a computer. Both interviews were digitally recorded and professionally transcribed.

In summary, the subject matter knowledge for teaching assessment was used to probe for participants’ subject matter knowledge for teaching. The interviews were used to further illustrate participants’ subject matter knowledge for teaching, to probe for pedagogical content knowledge for the Gas Laws, specifically to identify both the representations used in teaching the Gas Laws and any prior knowledge and alternate conceptions their students have of the Gas Laws. The collections of artifacts were used to aid in identifying the representations used in teaching the Gas Laws.

Data Analysis

The first research question, identifying chemistry teachers’ knowledge of chemistry representations with respect to the Gas Laws, was addressed through the
second interview and collection of artifacts. The interview was digitally audio-recorded and then professionally transcribed. The Gas Laws PCK Model (see Table 3.2) was used as the unit of analysis for this research question. Thus, the artifacts and transcripts were coded based on the four representations and subject matter knowledge for teaching present for the Gas Laws unit taught by each participant and then mapped onto the Gas Laws PCK Model (see Table 3.2). A partially ordered meta-matrix (Miles & Huberman, 1994) based on the Gas Laws PCK Model (see Table 3.2) served as the method of recording the coded artifacts and transcripts. As participants discussed their units on the Gas Laws, references to specific artifacts were usually mentioned. Thus, the artifacts were analyzed simultaneously with the interview data for each participant. Transcripts and artifacts were coded and recorded several times to “clarify” (Rubin & Rubin, 2005, p.207) what is meant by specific terms and concepts.

Cross case analysis occurred after each case was coded separately using the partially ordered meta-matrix (Miles & Huberman, 1994). Each of the four representations were highlighted a specific color in the meta-matrix. The use of color was helpful in making evident the kinds and amount of representations used by each participant in the teaching of their unit on the Gas Laws was evident. In addition, subject matter knowledge for teaching was partitioned and clustered (Miles & Huberman, 1994). From the partitioning and clustering, specific subject matter knowledge for teaching activities, such as experiments or topic selection, were noticed as similar or different for each participant.

The second research question, identifying chemistry teachers’ understandings of students’ alternate conceptions with respect to the Gas Laws, was addressed during the
first and second interviews by direct questioning of the participants. In the first interview
(see Appendix C), participants were provided with two novel scenarios where
participants were asked to provide student alternate conceptions. Participant responses
were placed in a meta-matrix. Notes based on partitioning and clustering (Miles &
Huberman, 1994) of the responses were recorded in the meta-matrix. Comparison with
Nussbaum (1985) and the Chemical Concept Inventory for each participant’s response
was also added to the partially ordered meta-matrix (Miles & Huberman, 1994).

During the second interview (see Appendix F), direct questioning of the
participants’ understandings of student alternate conceptions occurred. After the
participants had discussed their units on the Gas Laws with the researcher, participants
were directly asked if and how they take student prior knowledge and alternate
conceptions into account. These data were recorded in the interview field notes by the
researcher and added to the meta-matrix (see Table 3.4 below).

The third research question, identifying the structure of the chemistry teacher’s
subject matter knowledge for teaching regarding the Gas Laws, was addressed through
the subject matter knowledge for teaching assessment and first interview. Upon
completion of the assessment and first interview, each assessment was collected and
scanned. The first interview was digitally audio-recorded and professionally transcribed.
The assessment and transcribed interviews were coded simultaneously using a rubric.

The written assessment was scored based on a rubric (see Appendix D) using the
“ideal” answer as the maximum score of the rubric (Lin, Change & Lawrenz, 2000).
The researcher wrote the “ideal” answers. Carol Mindock-Wilkins, Ph.D. in
biochemistry at the University of Michigan, confirmed the “ideal” answers to the subject
Table 3.4: Part of the Meta-Matrix of Student Alternate Conceptions

<table>
<thead>
<tr>
<th>Participant</th>
<th>Q5: Removal of Air from flask via pump.</th>
<th>Q5: How to address in teaching.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erik</td>
<td>Erik has done this with his students before. Students might show a variety in size and spacing of molecules in the flask. Such as the molecules are really big with not much space if any between the molecules.</td>
<td>Use logic and talk about KMT and solids, liquids and gases. Give example of how the molecules in a solid are locked in a specific pattern and shape but are still moving. After heating to a liquid, the molecules are still relatively close together but not locked in a pattern. The cluster of dots would be more like a liquid than a gas. When heated to a gas, then they molecules start to really space out in the flask. Mentioned air in room and that students don't have to kneel to get the air. Air seems to be everywhere in the classroom--just like in the flask.</td>
</tr>
<tr>
<td>Julien</td>
<td>He says he has seen his students draw the air molecules as dots on bottom of flask--like they had sunk.</td>
<td>Show the correct answer. Then use his physical cues of &quot;hand to eye like a microscope&quot; to indicate particles are small and &quot;arms far apart&quot; to indicate the distance between particles is great. Particles are in constant, rapid, random motion. Also have students think of the air in the room, is it all on the bottom of the floor? Gas is all around equally filling the flask.</td>
</tr>
<tr>
<td>Matthew</td>
<td>Even distribution of air particles but below the flange in drawing. He did mention other alternative conceptions! He mentioned the flask might be blank--with nothing in it, there might be more dots in the flask, and not an even distribution of dots.</td>
<td>Show the right answer. Remind students that gas is always moving, have indefinite shape and volume, so gas should be filling container. When gas removed, no reason why gas wouldn't leave from all areas of flask. Talk through the properties of gases to have students logically come to the right answer. Perhaps have students act out the motion of particles in a confined area. An area of the room would be marked off and students would get into that area. Some students would be asked to leave the marked off area. Matthew would point out that students naturally evenly distribute themselves in both scenarios--just like gas particles.</td>
</tr>
</tbody>
</table>
Question about if the flask is sealed. Talks about how most of his students would show the correct idea. When pressed for "incorrect" answers, he mentions that students might show molecules clustered around the hole the air was pumped out of. He also mentions that students might think there are changes in pressure inside the flask depending on where in the flask pressure is measured. (Like near the hole where all of dots are clustered vs. in the far corners where there aren't any dots.) Also mentioned that pressure would not increase because there are less particles so less interference for collisions and the particles are moving faster because of the "sucking out" and less particles in the flask.

Would address by talking about the KM theory. Have students "look up the KM theory", "repeat", "review their answer". Look at the elasticity of the molecules that we consider under the Ideal Gas Law. Also remind students there is not an increase in speed of the particles and are still going to have perfectly elastic collisions. There will be no loss of energy.
matter knowledge for teaching assessment questions as well as the rubric. Using the rubric as a guide to “correctness” of content knowledge, participants were given a “score” for each question on the assessment. After the first scoring of participants’ responses, a fellow graduate student was asked to score the assessments and interviews. Scores were compared and discussed. The rubric was modified for clarity and to capture nuances across participants. The assessments and interviews were scored a second time by the researcher and an additional person. Scores were compared and only two scores of the twelve questions were not the same. Inter-rater reliability was established as 83%.

Limitations

The greatest single limitation to this study is the fact that the participants were not observed in their classrooms. The dynamic nature of PCK almost requires it to be seen in action. Thus, any analogies, demonstrations, examples, and illustrations (Shulman, 1986) that arise in the classroom during the act of teaching were not captured by this study. The narrative of the participants’ actions and statements outside of the act of teaching is subject to question.

While a pilot study was conducted, only two chemistry teachers, one a former teacher and the other a current teacher, participated. Issues that occurred during the collection and analysis of data were not discovered in the pilot study. For example, the interview protocol needed to be changed after the first interview. During the first interview, participants were asked at the end of the interview if and how they would use the apparatus presented in the two scenarios (see Appendix B). This became a problem during data collection. It became apparent to the researcher that asking about the apparatus at the end of the interview provided for short and sparse responses. Moving the questions about the apparatus to the middle of
During the interview when the apparatus had just been discussed provided for longer and more
detailed responses.

During data analysis of the subject matter knowledge for teaching assessment, it became obvious that participants were consistently having difficulty with the scenarios. During the pilot study, it was thought that that difficulty was a measurement of subject matter knowledge for teaching. However, during rubric development, it was uncovered that the participants had difficulty with the dynamic nature of the scenarios versus the end state portrayed in the Gas Laws themselves. A broader study of the details and nuances of the not only Boyle’s and Charles’ Law, but the other Gas Laws might have mitigated this issue.

While the researcher assumed that a fairly representative sample of participants would respond to the recruitment email, that was not the case. Only four chemistry teachers that met the specifications for the study responded. Thus, the researcher was limited to these four participants. As it turned out, the sample was biased. Only one participant teaches at a public school. The other three teach at private schools, two of which are Roman Catholic. Three of the four participants received their teaching license through the same post-baccalaureate program. All of the participants are male. Perhaps with a larger sample that included diversity, different or additional patterns and themes would have been appreciated.
CHAPTER FOUR
WITH-IN CASE FINDINGS

This chapter will present each case individually. Information from the subject matter knowledge for teaching assessment, semi-structured interview and collected artifacts for each participant is discussed here. After describing the background of the participant and the context within which he teaches, the subject matter knowledge for teaching responses will be compared to the ideal responses based on a rubric. Each participant’s PCK will be described through the representations targeted on the subject matter knowledge for teaching assessment as well as through analysis of each participant’s curriculum for the Gas Laws. Lastly, furthering the description of each participant’s PCK, knowledge of student alternate conceptions and how to address those conceptions in the classroom will be described. Cross-case analysis will be presented in Chapter Five.

Case One: Erik

Background

Erik received his bachelor’s of science degree in chemistry from a large Midwestern public university. Following graduation, he continued at the same university to earn a master’s degree in science education with a minor in biochemistry. Erik was hired as a full-time teacher immediately following completion of his student teaching at a large inner-ring suburban school in a large metropolitan area in the Midwest.

After Erik’s first year of teaching chemistry, he moved to Ashland High School, another large suburban high school but on the outer-ring of the metropolitan area. Ashland enrolls grades 10-12 and requires three full year, or 9 trimester, credits of science for
graduation. Approximately 15% of the students at Ashland are minority students. Erik reported that few minority students are enrolled in his chemistry classes.

Ashland has an atypical daily class schedule, combining block scheduling with traditional scheduling. Two days of each week are scheduled in the traditional manner with six classes of 55 minutes’ duration each. The remaining three days of the week feature block scheduling where each day includes four class periods of 80 minutes’ duration each. During the three days of block scheduling, each class period rotates out of the schedule such that any given class period meets only twice during the three block scheduled days. Thus, Erik sees each class only four times per week; however, two of the class meetings are of 80 minutes’ duration.

Students at Ashland typically enroll in a full year chemistry course during their junior year following a year of physical science and a year of biology. Ashland offers four levels of chemistry: STAR chemistry for those students who have low math skills, general chemistry for the typical junior, HP (high potential) chemistry for those students who have a particular interest in chemistry and AP (advanced placement) chemistry that follows the national curriculum designed for those students who are in the top 10% of their class. Erik has taught STAR chemistry, general chemistry and applied physics at Ashland. This year, he taught only general chemistry. The class size for general chemistry is 30-36 students per class.

When Erik joined the faculty at Ashland High School, the science department had a written curriculum for the general chemistry course that they had developed over the years. Literally, a set of large 3-ring binders was handed to Erik when he began teaching at Ashland. Erik chose to follow his colleagues’ curriculum and was freed from writing his
own curriculum for his chemistry course. The curriculum is fairly traditional and requires
students to use their textbook, *Chemistry* by Prentice-Hall, extensively.

*Subject Matter Knowledge for Teaching the Gas Laws*

During the first interview, Erik was asked to respond to three gas law scenarios
focused on three chemistry concepts: the kinetic molecular theory, Boyle’s Law and
Charles’ Law (See Chapter Three and Appendix B). Each of Erik’s responses was scored
using a rubric developed for this study (See Chapter Three and Appendix E). The following
table shows Erik’s scores, ranging from 0 at the lowest to 3 at the highest. Discussion of
each question and Erik’s response follow.

*Table 4.1 Erik’s Subject Matter Knowledge for Teaching Assessment Scores*

<table>
<thead>
<tr>
<th>Item</th>
<th>Score</th>
<th>Chemistry Concept</th>
<th>Targeted Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>1</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>1b</td>
<td>2</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2a</td>
<td>3</td>
<td>Identifying pressure/volume</td>
<td>Macroscopic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>differences</td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td>1</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2c &amp; 2d</td>
<td>1</td>
<td>Applying Boyle’s Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>2e</td>
<td>2</td>
<td>Applying Boyle’s Law</td>
<td>Graphic</td>
</tr>
<tr>
<td>3a</td>
<td>3</td>
<td>Predicting gas/volume changes</td>
<td>Macroscopic</td>
</tr>
<tr>
<td>3b</td>
<td>1</td>
<td>Applying Charles’ Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>3c &amp; 3d</td>
<td>2</td>
<td>Applying Charles’ Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>3e</td>
<td>3</td>
<td>Applying Charles’ Law</td>
<td>Graphic</td>
</tr>
</tbody>
</table>

*Kinetic Molecular Theory—Question 1a:*

Question 1a focused on the assumptions of the kinetic molecular theory and the
appropriateness of representations of gas molecules drawn within the closed container shown
in the test item. (See Appendix D for questions, ideal responses, chemistry concept
addressed by the question, and the representation that was targeted by the question).

Erik chose not to draw a picture to answer question 1a. Rather, he verbally described
his conceptions,
Okay, well, it's pulling on kind of random collisions taking place. I guess, the way that I envision is similar to pool balls in a pool table where they're bouncing and colliding. I guess you never really know for sure exactly where the molecule or the ball is going to go next. It depends on what it collides with and when. [There are] random collisions and bouncing off the walls of the container and off of each other. I don't think in terms of there's anything about the fact that there's oxygen and carbon dioxide. I don't know if there's any... I am just like mentally picturing all the molecules were like slightly different. But something, you know, like there's different shapes of molecules bouncing around. But I still cannot put the same image on them. Yeah. I would’ve—I mean, I guess the ball being perfectly round, you know, you don’t get a whole lot of, you know, like — I mean obviously they spin but not the same that like a — more of a bent shaped molecule would rotate around. So like that, then it would gain their momentum, and how it rotates would be different.

Of the many aspects of the ideal response, Erik mentioned only one, random collisions of the molecules, in his response. He did use an analogy of the pool balls to make a picture in his and in the interviewer’s mind. However, Erik does not elaborate on that analogy to include more aspects of the kinetic molecular theory, such as the facts that molecules are in constant motion and that molecules take up the entire space of the container. In describing how the molecules might look in the container, Erik mentions that carbon dioxide is a bent shape, which is not correct, and speculates as to how that bent shape will impact the momentum of the carbon dioxide.
Kinetic Molecular Theory--Question 1b

Question 1b focused on the assumptions of the kinetic molecular theory and differences in the behavior of the gas molecules within a closed container when the variable of heat was added to the scenario.

Again, Erik chose not to draw a picture to answer question 1b but rather verbally described his conceptions,

Okay, well, you know, similar to both situations but I would say no, [the molecules] are gaining kinetic energy from the heat and that is going to—I mean that they are moving faster. Then use the kinetic energy equation, $KE = \frac{1}{2}mv^2$, right? I would say that the mass is going to stay the same so the kinetic energy is going up, then it’s going to be the velocity that’s increasing. So now they’re still bouncing around and spinning and rotating and doing all that stuff but just faster. So there should [be] more collisions taking place with higher energy.

Erik mentions that random collisions are taking place between the molecules and the container. None of the other assumptions of the kinetic molecular theory are mentioned, such as there are equal number of molecules or moles of oxygen and carbon dioxide, with the average kinetic energy increasing, that means the average speed of each molecule increases which causes more pressure exerted on sides of container; molecules would take up the entire space of the container; there would be even distribution of $O_2$ and $CO_2$ in container.

Regarding the addition of heat, Erik focuses on kinetic energy and states that heat will cause the molecules to move faster. Erik cites the equation for kinetic energy, $KE = \frac{1}{2}mv^2$, using this equation to explain why the molecules are moving faster in the container. This appears to view molecular motion from a physics point of view; that is, Erik uses the symbolic
representation of the kinetic energy equation in a manner very familiar to the realm of physics.

*Identifying Pressure and Volume Difference—Question 2a and Kinetic Molecule Theory—*

*Question 2b:*

These two related questions focused on the ability of the participants to identify pressure and volume differences and explain their response for a novel situation (See Appendix D, 2a for question and ideal response. See Appendix B for scenario).

Erik responded to the prompt as follows,

Okay, so I would say that the pressure on the right hand side is going to increase and therefore it would push that oil level up so the volume of the trapped air would decrease. And the volume of the oil [in the glass tube] would go up. So I would — I mean, depending on how much air goes in there, you would imagine, the pressure to increase on that right hand side… I think it's the connection to the kinetic nuclear molecular theory about pressure is created by collisions of molecules. And if you are putting more molecules in there there’s going to be more collisions taking place. So more air, more collisions, higher pressure.

Here, Erik does mention that when air is added, more collisions take place which means higher pressure. Erik’s response, in comparison to the ideal response, seems focused only on the air trapped in the reservoir. The ideal response takes into account the air trapped in the reservoir and the air trapped in the glass tube. Erik does not mention what is happening to the particles in the glass tube. He answers the questions by only focusing on the air trapped in the reservoir. Erik seems to focus on only one “system”, that of the reservoir, instead of both “systems”, that of the reservoir and the glass tube. Erik also describes the “process” of
how the pressure and volume might change. He does not focus on the end point, that is, the new volume of the gas trapped in the glass tube due to the increased number of molecules of gas added to the reservoir.

*Applying Boyle’s Law--Question 2c and 2d:*

These questions asked participants to determine what data should be collected to be able to predict the volume of gas trapped in the glass tube for any given pressure in the reservoir. Participants needed to identify which two variables were changing, (volume and pressure). By identifying the two variables that were changing, participants automatically identified the constant variable (temperature) and the gas law being employed (Boyle’s Law). However, this was not a requirement. After the participants described this matter in general terms, question 2d asked participants to discuss in greater detail how they would determine the volume of gas trapped in the glass tube for any give pressure in the reservoir.

Erik correctly identified the two variables that were changing, the gas law being employed and the variable (temperature) that was being held constant. He also mentioned the assumption that the gas in the apparatus has to be an ideal gas. Erik’s response to question 2c was correct.

In addressing question 2d, Erik went on to describe how he would actually collect data,

Well, I mean, I guess if we are looking back again at the equations at the top before you're going to see that the temperature is held constant, then to get the pressure we would need to know the — what did we click to know the volume—So then we would need to know the pressure change. So it’s yes, the temperature is constant and we would just need to know the pressure and the volume. Boyle's Law?
Erik referred back to the Gas Law equations that were provided at the beginning of the written assessment. Erik refers to the equation $P_1V_1 = P_2V_2$ (T is constant) to determine which variable is being held constant and which variables are changing. It seems that Erik is uncertain of how to collect the data. He states that volume would need to be known. However, he refers to the need to know the pressure change, not the initial pressure and the ending pressure. Also, Erik mentions Boyle’s Law, but in a questioning manner as though he were not sure if Boyle’s Law is the gas law to use in this situation. It is difficult to determine if Erik is using the equation as a crutch and just stating variables based on the equation or if he is really answering the question.

*Applying Boyle’s Law--Question 2e*

This question asked participants to graph the data that they would have collected from the previous question. Erik’s response to this question not only included a graph for a “real” gas but for an “ideal” gas as well. He stated,

So I mean, if we were looking at pressure and volume, pressure and volume before changing — we're changing the pressure and looking to see how the volume changes as a consequence. So, like how would I plot the data? So the — the variable that we will be changing would be the pressure, so we put that across the x [axis]. And then the one that’s changing as a result we’ll put along the y [axis], so I will put the volume. I would expect to see that as the pressure increases, the volume would decrease. And again if we are looking at the — at the ideal gases, you know, if it’s truly following the equation of the linear relationship... So slanting from the, you know, top left to the bottom right. So pressure goes up, volume goes down. But real gases, you know, we don’t see it. Maybe for a little while, we would see a linear
relationship but then it would sort of flatten out towards the bottom. So it’s start
linear then kind of, yeah, plateau or flatten out towards the bottom.

*Figure 4.1: Erik’s Graph for Question 2e of the Written Assessment*

Erik’s graph compares a “real” gas to an “ideal gas”. He plotted pressure on the x-axis when it should ideally be plotted on the y-axis. Also, Erik’s graph for the “real” gas is a graph with two intersecting lines of different slopes rather than a power-inverse curve.

*Predicting Volume of Gas Changes—Question 3a and Applying Charles’ Law—Question 3b:*

A new apparatus and scenario were presented to the participants for this series of questions. (See Appendix B for the apparatus). These questions asked participants to predict the direction the oil plug would move in the apparatus if the apparatus were to be moved to a colder environment. After the prediction, participants were asked to explain their reasoning. Erik correctly predicted the motion of the oil plug toward the left when the apparatus is moved to a colder environment. However, his explanation deviated from the ideal answer.

Erik’s explanation was stated as follows,

Okay, well, my reason would be that the amount of gas inside of the flask under colder temperatures would start to move slower and so that there'd be less collisions which as a result would lower the pressure inside the flask and pressure outside staying at the atmospheric pressure would, I assume, would be greater than the
pressure inside the flask. And so the pressure outside, I would imagine to push that oil drop in this diagram to the left or closer towards the flask, as it moves towards, yeah, toward the end of this flask.

Erik did not correctly identify pressure as the constant variable. Although immediately upon moving the apparatus to a colder environment pressure is not constant, eventually pressure does equalize between the outside of the flask and the inside of the flask. Thus, as the flask reaches the same temperature as the environment, pressure is the same as the environment outside the flask. Thus, pressure is the constant variable. Erik starts his explanation of the scenario without realizing that pressure does eventually equalize and is thus constant. Erik focuses on the “process” of how the oil drop moves where pressure, temperature and volume are all changing. He chose temperature and pressure to be the variables changing, leaving volume as the constant variable. Erik assumes that volume is constant, presumably based on the fact that the total volume of the flask and tubing does not change. Thus, temperature and pressure must be the changing variables, as Erik sees it. However, the “volume” in the scenario is actually the volume of the gas trapped in the apparatus, which does change as the pressure equalizes. Thus, the changing variables are actually volume of the gas trapped in the apparatus and temperature.

*Applying Charles’ Law--Questions 3c & 3d*

These questions asked participants to determine what data should be collected and how to collect those data for volume in the apparatus for any given temperature. While Erik was not able to correctly identify pressure as the constant variable and volume and temperature as changing in question 2b, he did correctly identify the need to measure volume and collect volume data for questions 3c and 3d,
Okay, so you need to know temperature, the normal room temperature, and yeah, I guess the volume that occupies, so, the volume of the flask and the volume that the tube occupies. And then seeking out temperature and volume and—I would imagine that the pressure is going to stay the same inside the flask because then that is the whole reason why the oil [drop] moves so the pressure can still the same inside [the flask] compared to outside [the flask]. So if we knew the temperature and the volume, before we move to the other room and then we know the temperature of the new room, we should then be able to calculate the new volume. And so—so we have to plug in that equation, we calculate the new volume, we should then be able to predict whether it’s going to move — the oil drop is going to move to the right or to the left, increasing volume would move it to right; decrease in volume, it would move to the left. Now we have a nice little, you know, marks on there [the tubing], to tell us how to read the volume, then we should be able calculate or predict where we go.

In the previous question, Erik said that pressure and temperature where the changing variables. However, in the present response, it seems that Erik understands this scenario to be about volume and temperature as the changing variables. He even mentions that pressure will remain constant; “that the pressure can still the same inside compared to outside.” Erik does not describe how he would calculate the new volume of the apparatus but he does seem to understand that he must collect volume and temperature data to answer the question.

*Applying Charles’ Law--Question 3e*

This question asked participants to graph the data that was described in question 3d. Erik correctly described the graph that would result from his data collection described in the previous question, 3d.
Figure 4.2: Erik’s Graph for Question 3e of Written Assessment

He placed volume on the y-axis and temperature on the x-axis and described an increasing linear line graph. Erik did not label his axes. Thus, the y-intercept of the line cannot be zero if the temperature is measured in Celsius. The y-intercept can only be zero if the temperature scale is in Kelvin. The Kelvin scale will allow for zero volume at zero degrees Kelvin. This is absolute zero. However, if temperature is measured in Celsius, zero volume at zero degrees Celsius is not possible.

Pedagogical Content Knowledge

Pedagogical Content Knowledge (PCK) was assessed through two avenues in this study. The first avenue was to ask the participants if they would use in their own classrooms the apparatus presented in the first interview. Follow up questions asked how and why the apparatus would or would not be used. This line of questioning gave participants the opportunity to talk about their PCK in relation to the novel apparatus, thus demonstrating their understanding of the subject matter knowledge for teaching underlying the concepts for which the apparatus can be used, their pedagogical knowledge regarding the use of the apparatus, and their knowledge about learners in how the participants would present the apparatus and what their students would be asked to do with the apparatus. Here, the dynamic nature of PCK can be seen and, perhaps, documented.
The second avenue of assessing PCK was to ask the participants how they actually teach their unit on the Gas Laws. This information was obtained in the second interview. Participants were asked to provide lecture notes, worksheets, experiments and assessments in addition to describing in detail how they teach their Gas Law unit. By discussing their practice and displaying artifacts, participants were able to talk through their thinking and decision making process that forms the foundation of lesson planning and execution.

These two methods of assessing PCK, discussion about the possible use of new apparatus and descriptions of actual classroom practice, illuminate the participants’ use of representations and their understanding of student conceptions.

*Use of Apparatus Presented in Scenarios*

During the first interview, participants were asked if they would use in their classrooms the apparatus presented in the scenarios, if they had access to it; and further, how and why they would use or not use the apparatus.

Regarding the first apparatus, the oil reservoir and glass tube (See Appendix B), Erik responded that he would use the apparatus in his classroom because the students could read a pressure gauge and could also read the volume of the air trapped in the glass tube by using the scale behind the tube. He sees this apparatus as an improvement over the lab he currently uses to illustrate Boyle’s Law. Erik’s current Boyle’s Law lab apparatus is a syringe with some air trapped in it and a two-liter soft drink bottle placed on top of the plunger of the syringe. Water added to the bottle at the rate of 100 mL at a time is a proxy for pressure while the air trapped in the syringe is the volume of the gas. Erik said he would “like to be able to pull numbers off of an instrument. It looks nice and fancy.”
If he could, Erik would like to use the oil reservoir apparatus as an experiment to replace the current soft drink bottle experiment so that students could collect pressure and volume data that was measured directly as opposed to data as a proxy, such as number of milliliters of water for pressure. He thinks that by using measured data that the inverse relationship between pressure and volume would be more obvious to his students. Erik would also like to use the apparatus to identify the differences between ideal and real gases. Erik does not state in the interview how he would use the apparatus to illustrate this.

Regarding the second apparatus, the Erlenmeyer flask and tubing with the oil plug (See Appendix B), Erik again responded in the affirmative that he would like to use this apparatus in his classroom because students could read volume markings directly from the tubing, assuming markings were made on the tubing prior to or as a part of the experiment. Erik would use the apparatus in small lab groups to illustrate the “volume - temperature relationship with qualitative aspect first and then bring in the calculations and hopefully the calculations match with the experiment.”

**Representations in Teaching Practice**

In order to understand the representations used by Erik in his teaching practice, it is necessary to understand how he teaches his unit on Gas Laws. The following table outlines Erik’s curriculum in brief along with the representations focused on during each activity.

*Table 4.2: Erik’s Curriculum of Gas Laws Unit*

<table>
<thead>
<tr>
<th>Day 1</th>
<th>Curriculum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Students read chapter and take notes. Students take a 10-15 item pre-test on concepts in chapter after reading/note taking.</td>
</tr>
</tbody>
</table>
Day 2
Packet for entire unit given out.
1. Lecture and Notes on Boyle’s Law.
2. Demo--Boyle's Law--Syringe Demo (Show syringe and as the plunger is pushed the volume of air in syringe gets smaller.
3. Problems for each law.
Day 3
1. Boyle's Law experiment with syringe and 2L pop bottle full of water as a proxy for pressure.
2. Graph data
Day 4
Charles' Law
1. Lecture and Notes on Charles’ Law
2. Balloon/flask demo
3. Problems assigned
Day 5
Gay-Lussac's Law
1. Lecture and Notes
2. Demo with corked flask with water in it. Heat the water in flask and cork pops off.
3. Problems assigned
Day 6
Combined Gas Law
1. Usually notes and problems
2. Demo (Sometimes) with heated pop can turned upside down in ice water
Day 7
Dalton's Law of Partial Pressures
1. Usually notes and problems
2. Doesn't demo. Talked about seeing applets but hasn't found a "good one"
Day 8
Ideal Gas Law
1. Notes, problems
2. Demo (sometimes) Shows flat basketball and talks about "adding moles/air"
Day 9
Ideal Gas Law
1. Experiment to find R
Day 10
Review
Day 11
Test

The four representations, that is, Macroscopic, Particulate, Symbolic, and Graphic, were used to examine Erik’s teaching of the kinetic molecular theory, Boyle’s Law and Charles’ Law. Classroom instruction techniques such as experiments, demonstrations,
activities, assignments and summative assessments were examined to determine the types of representations used for the specific student action.

*Macroscopic Representation.*

Macroscopic representations are seen only in Erik’s instruction for Boyle’s and Charles’ Laws. When teaching Boyle’s Law, Erik uses a demonstration and an experiment to illustrate the law macroscopically. The demonstration involves the use of a syringe: the plunger is placed at a specific volume, the syringe is then capped, and pressure is applied to the plunger forcing the plunger further into the syringe. Eric then asks his students what is happening to the volume of the gas trapped in the syringe. Students readily recognize the decrease in the volume of the air trapped in the syringe as more pressure is applied.

The experiment that Erik uses to illustrate Boyle’s Law is a syringe with a certain volume of trapped air in it. The syringe is capped. Students then clamp the syringe into a clamp mounted on a ring stand. An empty two-liter soft drink bottle is placed on top of the plunger. Water, added 100 mL at a time to the bottle, acts as a proxy for pressure. Volume of the trapped air in the syringe is read directly off of the syringe. In this experiment, while data are collected, Erik’s main objective is for students to visualize that as pressure is increased in the form of weight of water, the volume of a trapped amount of air decreases in the syringe. Erik calls these types of demonstrations and labs qualitative—where students can see what is happening without using any mathematical calculations.

When teaching Charles’ Law, Erik uses a demonstration— a macroscopic representation. A latex balloon is placed over the opening of an Erlenmeyer flask that has a few milliliters of water in the bottom. The flask is then heated on a hot plate. As the water begins to heat in the flask, the balloon begins to inflate. After a period of time, the flask with
the balloon still attached is placed in an ice water bath. As the flask cools, the balloon gradually deflates and ends up actually inside the flask while still attached to the mouth of the flask. Data is not collected from this demonstration. Erik uses this demonstration to illustrate the relationship between temperature and volume. While Erik does use a macroscopic example for each of the gas laws, he does not include the macroscopic representation in the assignments nor the summative exam.

**Particulate Representation.**

When teaching the kinetic molecular theory, Erik uses an analogy of “pool balls on a pool table colliding—you never know where the ball will be—it depends on the collisions.” Erik also will sometimes use computer simulations such as applets to illustrate moving particles. Erik does not use the particulate representation when teaching Boyle’s Law or Charles’ Law. The particulate representation does not appear as part of any assignment or the summative exam.

**Symbolic Representation.**

During the instruction of Boyle’s and Charles’ Law, Erik focuses on the mathematical relationships of direct and indirect proportions. Students are asked throughout the Gas Law unit to identify direct and indirect relationships based on mathematical equations. Boyle’s law is an example of an indirect relationship between pressure and volume. Charles’ Law describes a direct relationship between volume and temperature. Erik states that he reinforces these concepts heavily. The artifacts do not support this statement. However, without observing his classroom, it is difficult to state definitively whether or not he does emphasize direct and indirect relationships between variables in the gas laws. He also assigns mathematical problems where students are given three variables for Boyle’s and
Charles’ Law and are asked to mathematically solve for the fourth variable. Erik also changes units for volume, pressure, and temperature so that students must also know how to convert between different volume, pressure, and temperature units.

*Figure 4.3: Example of an Assignment Used by Erik*

In addition to homework problems, these types of mathematical problems occur on the summative unit exam.

*Figure 4.4: Example of a Summative Exam Question Used by Erik*

*Graphic Representation.*

Erik does not use graphic representations heavily. Students are asked to construct one graph from the experiment with the syringe and water in the two-liter soft drink bottle to illustrate Boyle’s Law. It does not appear that Erik revisits the graphic representations after the experiment. Graphic representations are not part of any assignment, the summative review assignment, or the summative exam.

*Student Conceptions in Teaching Practice*
As part of the first interview, participants were asked to predict student conceptions to two scenarios involving the behavior of gases—primarily focusing on alternate conceptions of the kinetic molecular theory.

The first scenario (See Appendix B) is a sealed Erlenmeyer flask that is filled with air. An evacuation pump is connected to the flange in the flask and some of the air is pumped out. The pump is removed from the flange. Participants were asked to draw the flask and air particles in the manner they thought their students would illustrate the air particles in the flask after some of the air had been removed.

At the beginning of this scenario, Erik stated that he has presented his students with this scenario before. He tried to remember what he actually saw his students produce. He seems to recall that some of his students addressed the scenario correctly,

Let’s see, I have done this with them. What did they do? There’s lot of different things. Some of them I think did a pretty good representation of showing just kind of randomly throughout, you know, when I did this with them.

After a while, Erik identified two alternate conceptions his students might present. Erik recalls,

How big they [the molecules] were and how much space there was between them, right up to the sides of the molecules. So sometimes they’re [the molecules] really big and the space between them was very little.

Erik predicted that his students might show a variety in size of the air particles and a variety in the space between those particles in the flask.

When asked about how he would address these alternate conceptions in his teaching, Erik responded,
I would try to — I guess like talk about the fact that, yeah, I would I address that— I think what I currently do like when I talk about the kinetic molecular theory and phase changes and talk about like how solids, you know, the molecules and the atoms are all kind of locked in a specific pattern and shape, but they are still moving. And then after, you know, heat up to a liquid. Then they still are relatively close together, but they are not in a locked pattern and they would roam move freely. And that would, to me, describe kind of like what you were mentioning that all the dots being at the bottom of the flask, as I try to make a connection that that's more similar to what a liquid would look like and then as it’s heated up even further into gas then that’s when they start to really space out within and build the place. And then I guess, I will try to use some logic with them about you know, gases in the room right now, you know, like to breathe the oxygen, you have to get down on the floor to breathe or you can, you know, be standing where you are. You know, is there parts of the room that it's easier to breathe then other parts, you know. So that hopefully, I kind of make sense of them of like, yeah, I guess there's gas everywhere, not just on the bottom of the container.

The second scenario (See Appendix B) showed a cross-section of a steel tank full of hydrogen gas. The hydrogen molecules are drawn as dots in the tank. Again, participants were asked to predict what they think their students will draw for the hydrogen molecules in the cross-section when the tank is cooled. Erik predicted that his students might draw the dots sinking down to the bottom of the steel tank. However, Erik mentions that the gas might be shifting to the liquid phase if it gets cold enough; therefore, he states that the drawing of the sinking molecules would then be valid.
To address this student alternate conception in his classroom, Erik says,
How I would address that would be, you know, I would try to, you know, maybe the same as I said before you know like, if you're in a cold room—does all the air sink down to the bottom of the room or can you still breathe at, you know, the top of the room? Like maybe, I don't know, if you were like, well I can get somewhere cold. I get to go outside, the deal is like, if you have to crawl on the ground to breath or can you just walk around normal? So I think that's how I would try to use logic or reason with them. I was just to try to pull in experiences of that there —Maybe I'll of think about it that way but they are at least familiar with it.

Erik likes to use students’ experiences to help explain science concepts. The logic seems obvious to Erik. However, he did not mention how his students respond to his arguments to counter their alternate conceptions. He concluded that using logic was appropriate for dispelling alternate conceptions.

Case Two: Julien

Background

Julien was a double major in undergraduate school, completing a bachelor’s of science in chemistry and a bachelor’s of arts in music. After graduation he pursued music academically and professionally, studying in Europe and performing worldwide. Eventually, he returned to his interest in science, enrolling in a post-baccalaureate program at a large public university in the Midwest where he earned a Master’s of Education in science education.

Julien began his teaching career 14 years ago in a rural high school in the Midwest where he taught chemistry and physics. After several years, he moved to Two Rivers High
School, a private Catholic school in an urban metropolitan area in the Midwest. Two Rivers is a 9-12 college-preparatory high school located in the heart of a large metropolitan area in the Midwest. Approximately 600 students drawn from the metropolitan area and beyond attend Two Rivers, which, according to its web site, “attract[s] students from the broadest possible mix of backgrounds”. Julien reports that his school, and his classroom, is very diverse in terms of race, religion and socio-economic backgrounds.

Two Rivers has a daily schedule of eight class periods of 44 minutes each. Students have a maximum of seven class periods; the eighth period is reserved for lunch. Unlike the public schools in this Midwest state, only one year of physical science and one year of biology are required for graduation. However, since Two Rivers is a college-preparatory high school, most students do enroll in three or four years of science. Julien’s students typically take chemistry in their junior year.

During his eight years at Two Rivers High School, Julien has taught only chemistry and Honors chemistry. Honors chemistry is offered for the students who hope to pursue a career in the sciences. Class sizes for Julien’s chemistry courses range from 17 to 27 students with the Honors course attracting the larger number of students. For this study, Julien’s chemistry course was the focus.

Julien’s chemistry course uses *Chemistry in the Community* published by the American Chemical Society. Julien follows the curriculum of the text with an occasional deviation, such as substituting a different experiment for an experiment suggested in the text. Julien writes his own chapter quizzes and unit exams.
Subject Matter Knowledge for Teaching the Gas Laws

During the first interview, Julien was asked to respond to three gas law scenarios focused on three chemistry concepts: the kinetic molecular theory, Boyle’s Law and Charles’ Law (See Chapter III and Appendix B). Each of Julien’s responses was scored using a rubric developed for this study (See Chapter III and Appendix D). The following table shows Julien’s scores, ranging from 0 at the lowest to 3 at the highest. Discussion of each question and Julien’s response follow.

Table 4.3: Julien’s Subject Matter Knowledge for Teaching Assessment Scores

<table>
<thead>
<tr>
<th>Item</th>
<th>Score</th>
<th>Chemistry Concept</th>
<th>Targeted Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>2</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>1b</td>
<td>2</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2a</td>
<td>3</td>
<td>Identifying pressure/volume differences</td>
<td>Macroscopic</td>
</tr>
<tr>
<td>2b</td>
<td>1</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2c &amp; 2d</td>
<td>0</td>
<td>Applying Boyle’s Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>2e</td>
<td>3</td>
<td>Applying Boyle’s Law</td>
<td>Graphic</td>
</tr>
<tr>
<td>3a</td>
<td>3</td>
<td>Predicting gas/volume changes</td>
<td>Macroscopic</td>
</tr>
<tr>
<td>3b</td>
<td>1</td>
<td>Applying Charles’ Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>3c &amp; 3d</td>
<td>3</td>
<td>Applying Charles’ Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>3e</td>
<td>0</td>
<td>Applying Charles’ Law</td>
<td>Graphic</td>
</tr>
</tbody>
</table>

Kinetic Molecular Theory—Question 1a

Question 1a focused on the assumptions of the kinetic molecular theory and the accuracy of drawing gas molecules within a closed container. Julien chose to draw while he explained his thinking for this question (See Figure 4.5 below).
In the drawing, Julien has equal numbers of oxygen and carbon dioxide molecules with lines coming out from the molecules to indicate random motion. There is an even distribution of molecules in the flask. Julien has drawn oxygen as diatomic and the carbon dioxide as linear with the carbon atom in the center of the molecules and the oxygen atoms on either side of the carbon atom.

Julien: I am a visual learner so I will draw the diatomic oxygens (see paper). Evenly distributed in this Erlenmeyer flask. (Counts in French up to 8). And then the carbon dioxides…(makes noises as he draws—counts in French up to 8) and to show motion, I’m going to put 2 lines showing that they are constantly, rapidly, randomly moving around “zee Erlenmeyer flask” (he says with a German accent—and making whooshing sounds as he draws the lines indicating motion).

Interviewer: You had mentioned that they were evenly distributed in the flask. Can you tell me your reasoning behind that drawing?
Julien: Um…gases at the same temperature and pressure seem to behave in similar manners and, you know, carbon dioxide would be more dense, so maybe carbon dioxide would be closer to the bottom (of the flask). I guess that I am more showing that they are moving about and bouncing off the inside of the container.

However, in explaining his drawing Julien commented “gases at the same temperature and pressure seem to behave in similar manners and, you know, carbon dioxide would be more dense so maybe carbon dioxide would be closer to the bottom (of the flask)”. The density of carbon dioxide and the position of the carbon dioxide in the flask vary from the ideal response for this question.

*Kinetic Molecular Theory--Question 1b*

Question 1b again focused on the assumptions of the kinetic molecular theory and the accuracy of drawing gas molecules within a closed container, but now with the variable of heat added to the scenario. Julien drew his conception of oxygen and carbon dioxide being heated in the flask (See Figure 4.6 below).

*Figure 4.6: Julien’s Drawing for Question 1b of the Written Assessment*
Julien drew eight diatomic oxygen molecules and eight linear carbon dioxide molecules randomly scattered throughout the flask. This drawing is very similar to the drawing Julien drew for question 1a. As Julien explained this drawing he stated,

And then I’ll put 3 lines behind them showing that they are moving faster. Then, then, carbon dioxide (counting in French up to 8). So they are moving faster inside this Erlenmeyer flask. AAAHHHH, a higher kinetic—a higher temperature. A higher kinetic energy—more collisions—moving about faster.

Julien exhibits the majority of components of the kinetic molecular theory in his drawings and explanations. He does not mention that there are no interactions between particles and that the volume of the gas particles is assumed to be zero.

**Identifying pressure and volume differences--Question 2a and Kinetic Molecular Theory—Question 2b**

These questions focused on the ability of the participants to identify pressure and volume differences and explain their response for a novel situation (See Appendix B, 2a). Julien correctly predicts an increase in the level of oil in the glass tube of the apparatus. As Julien explains his reasoning,

The air particles in the glass tube before the air is added to the reservoir, are just moving about again and constant, rapid, random motion--Hitting each other and the sides in there. Same thing in the reservoir, the gas particles are moving about. And I suspect that after the air comes into the reservoir---(voice goes up like a new thought)--Gas particles in the reservoir are moving kind of the same, where as the gas particles that are trapped between the oil and in the glass tube, they will moving the
same, maybe, have the same, the same kinetic energy but the pressure will increase [because of smaller volume] and they will bouncing into each other more.

Julien’s response to the question addresses most of the aspects of the ideal response. He does mention that the gas molecules trapped in the glass tube and the oil reservoir are in constant, random motion colliding with each other and with the sides of the container. He also notes an increase in pressure on the oil in the reservoir due to an increase in the amount of air particles being added to the system. What Julien does not explicitly take into account is that the temperature of the system is being held constant and that he must assume that the air trapped in both the reservoir and the glass tube must behave ideally. In addition, Julien mentions kinetic energy of the gas molecules trapped in the glass tube and the oil reservoir and he seems to get lost in this thought during his explanation.

*Applying Boyle’s Law--Question 2c and 2d*

In answering the general question 2c about what data would he collect for volume of gas trapped in the glass tube for any given pressure, Julien responded,

I think the pressure in the reservoir would be, you maybe want to know that and then maybe the volume of the gas that is in the reservoir and then the volume in the glass tube and that would be enough information to calculate the pressure in the glass tube using Boyle’s Law. So, \( \frac{P V_2}{V_1} \), and if also, if the temperature is staying constant.

This response is very similar to the ideal response. Julien mentions knowing the pressure in the reservoir, volume of gas in the reservoir and the volume of gas trapped in the glass tube. Knowing those three variables, Julien would use Boyle’s law to calculate the fourth variable, the pressure on the gas molecules trapped in the glass tube. Julien also takes into account the fact that temperature of the system must be constant.
In answering question 2d, Julien seems more uncertain about his responses. He states,

That is from the data to calculate the pressure in the glass tube. Um…Knowing how much air is added…uuuhhhhh…the pressure gauge reading, the volume here (pointing to reservoir)… …

There are a couple of longer pauses during Julien’s explanations of what data to collect and how to collect the data. The long pauses in Julien’s response imply that Julien is uncertain of how to collect data for this scenario.

*Applying Boyle’s Law--Question 2e*

In response to being asked to graph the data he might collect from question 2d, Julien said, “What would you plot if you were to graph the data? P, V. Uuuuhhhhh…(8 second pause)…Maybe p over v….” In response to being asked what the graph might look like if you were to draw it, Julien said, “AAhohhh, asymtotic? (making sounds as he draws the graph on the paper---getting smaller-----getting bigger----) Something like that.” (See Figure 4.7).

*Figure 4.7: Julien’s Drawing for Question 2e of the Written Assessment*

Julien’s long pauses and self-questioning tone in his response imply uncertainty with this scenario.
Predicting Volume of Gas Changes--Question 3a and Applying Charles’ Law--Question 3b

These questions asked participants to predict the direction the oil plug would move within the apparatus, in the event that the apparatus were to be moved to a colder environment, and to explain the reasoning behind their prediction. Julien correctly predicts that the oil plug will move toward the left when the apparatus is taken to a colder environment. However, he identifies temperature and pressure as the changing variables for the apparatus instead of the correct response of temperature and volume. Julien said,

I am assuming you are putting it together in the room and then um...you take it outside and there is this amount of trapped gas cools...the pressure inside the flask is going to go down and the outside air pressure will push that drop of oil towards the flask.

Applying Charles’ Law--Questions 3c & 3d

These questions asked participants to determine what data should be collected and how to collect data for volume in the apparatus for any given temperature. In the previous question, Julien said the changing variables were temperature and pressure. However, when asked to determine what data to collect and how to collect it, he responded with data collection for temperature and volume. There seems to be some trepidation in Julien’s response. For example,

What data would you collect to know where the oil drop would be when the apparatus is in a room at 120 degrees? ...I guess I could collect ...let’s see...(6 sec pause) ...I guess you could put a ruler behind this glass tube...and mark it off...and then if you...(3 second pause) knew...you knew its placement at a certain...(3 second pause) ...you know maybe I would have to collect the data first, going from inside to outside
to know how the drop moves in the tubing…and then…(14 second pause)…I would know how much its moving or that temperature change and then I could predict movement at this much higher temperature.

When Julien suggests that a ruler could be put behind the glass tubing and marks could be made on it to show the placement of the oil plug at various temperatures, he is speaking about volume instead of pressure. Julien has abandoned his idea of pressure being the variable to change. However, he does not explicitly tell us that the marks on the glass tubing are a proxy for volume. It is possible that Julien thinks that marks on the glass tubing are a proxy for pressure.

Julien’s response quoted immediately above contains a number of pauses lasting several seconds each. Also, Julien begins a thought about putting a ruler behind the glass tubing but abandons it for the idea of doing the experiment qualitatively to see what would happen first. It is as if he doubts his prediction from question 3a.

Applying Charles’ Law--Question 3e

This question asked participants to graph the data that they would have collected from the previous question. Julien responds correctly regarding the shape of the graph, a positive increasing linear line (See Figure 4.8).

Figure 4.8: Julien’s Graph for Question 3e for the Written Assessment
However, Julien is uncertain as to what variables to plot on the graph. Again, Julien does not see the displacement of the oil plug as volume of the gas in the apparatus and focuses on using a distance measurement to graph against temperature.

It should be a linear line if you graph it. Let’s see, mmmm….maybe temperature on the x-axis…and then ahh…(2 second pause) guess…(17 second pause) would be centimeters? The oil drop…(4 second pause)…maybe millimeters?

Pedagogical Content Knowledge

Pedagogical Content Knowledge was assessed through two avenues in this study. The first avenue was to ask the participants if they would use in their classrooms the apparatus presented in the first interview. Follow up questions asked how and why the apparatus would be used or not used. This line of questioning gave participants the opportunity to talk about their PCK in relation to the novel apparatus, thus demonstrating their understanding of the subject matter knowledge for teaching underlying the concepts for which the apparatus can be used, their pedagogical knowledge regarding the use of the apparatus, and their knowledge about learners in how the participants would present the apparatus and what their students would be asked to do with the apparatus. Here, the dynamic nature of PCK can be seen and, perhaps, documented.

The second avenue of assessing PCK was to ask the participants how they actually teach their unit on the Gas Laws. This information was obtained in the second interview. Participants were asked to provide lecture notes, worksheets, experiments and assessments in addition to describing in detail how they teach their Gas Law unit. By discussing their practice and displaying artifacts, participants were able to talk through their thinking and decision making process that forms the foundation of lesson planning and execution.
These two methods of assessing PCK, discussion about the possible use of new apparatus and descriptions of actual classroom practice, illuminate the participants’ use of representations and their understanding of student conceptions.

Use of Apparatus Presented in Scenarios

Regarding the first apparatus, the oil reservoir and glass tube where air is added to the reservoir (See Appendix B), Julien initially said he would use the apparatus in his classroom, though only as a demonstration because his high school would be able to afford only one. As a demonstration, Julien would involve his students in reading the measurements of the pressure in the oil reservoir from the gauge and the volume of the trapped gas in the glass tube from the scale behind the glass tube. Julien’s objectives for this lesson using this apparatus would be,

Boyle’s law. hhhmmmm….and that an inverse relationship. And ahhhh….lots of times I find the students…they have an idea of [what] inverse and directly proportional is…hard to grasp sometimes and we get through that using some graphing exercises also. We do something similar to this but with books and a trapped amount of gas in a syringe and you stack the books and that is the pressure of the books on there and you watch the volume and then we graph. We do a simple graph and that helps them see that relationship also. We just, we focus on collecting the data and, and then drawing the graph. and….aaahhh…it is pretty clear that the volume of the gas is going down. We talk about the particles, that is hard for them to grasp too. A…grasp also…the kinetic, the parti…the particulate mode….the particulate nature of the particles and how they are moving. We try to talk about that and that doesn’t sink in until later. I think we probably spend time answering a few
questions just to reinforce that [as] the pressure increases the volume gets smaller and then we make the graph.

The second apparatus, the Erlenmeyer flask and tubing with the oil plug where the apparatus is moved from different temperature environments, was also proposed for classroom use. Julien said he would use this apparatus in his classroom. However, he went on to describe a similar apparatus that he used from the textbook, where a capillary tube has air trapped in it by an oil plug. The capillary tube is attached to a ruler and then the entire apparatus is submerged into different temperature water baths. Julien does not like the capillary tube experiment because it is messy and the students had trouble being accurate with marking the placement of the oil plug on the capillary tube since it is so small. Julien then offered as an example the experiment he prefers to use in his classroom.

What I do instead is pressure and temperature experiments …um…with an enclosed amount of gas. I forgot what you call those things, it is a ball of gas with a pressure gauge on it. So it is an amount of trapped gas. We have 4 different temperatures and that is what we graph. We use that also to show that relationship and then also extrapolate backwards to absolute zero.

Notice that Julien focuses on pressure and temperature in his example. The Erlenmeyer flask apparatus presented in the scenario is to illustrate Charles’ Law, where pressure is constant and the volume of the trapped air in the flask and tubing and the temperature are the variables that are changing.
**Representations in Teaching Practice**

In order to understand the representations used by Julien in his teaching practice, it is necessary to understand how he teaches his unit on Gas Laws. The following table outlines Julien’s curriculum in brief along with the representations focused on during each activity.

**Table 4.4: Julien’s Curriculum of Gas Laws Unit**

<table>
<thead>
<tr>
<th>Day</th>
<th>Curriculum</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Demos--Exploring properties of gases. There are 10 demos that lead students to identify properties and behavior of gases. These include mass, volume, air exerts pressure in all directions, temperature effects volume &amp; pressure, etc.</td>
<td>Macroscopic</td>
</tr>
</tbody>
</table>
| 2    | 1. Graphing atmospheric data of temp vs altitude and pressure vs altitude but data table has mass and total molecules.  
2. Questions to answer with graphs | 1. Graphic  
2. Questions are graphic with 1 question having to do with particulate |
| 3    | 1. Pressure= Force/area  
2. Examples of high heels vs tennis shoes | 1. Symbolic  
2. Macroscopic |
| 4    | 1. Barometers-electric  
2. Metrodome as an example and how weather effects Dome itself. | Macroscopic |
| 5    | KMT  
1. Balloon inflation-Air particles  
2. Hand motions for each part of KMT (4 bullets) in text. | 1. Macroscopic and Particulate  
2. Particulate |
| 6    | Boyle’s Law  
1. Lab--Boyle's Law with syringe and books as a proxy for pressure  
2. Graph data  
3. Problems on back of lab | 1. Macroscopic  
2. Graphic  
3. Symbolic |
| 7    | Charles’ Law  
1. Demo-dry ice in balloons. Uses to reinforce KMT  
2. Demo/Lab--Cu bulb with pressure gauge into different temperature baths.  
3. Graph the data  
4. Graph used to extrapolate to absolute zero | 1. Macroscopic and Particulate  
2. Macroscopic  
3. Graphic  
4. Graphic |
| 8    | Charles' Law  
1. Problems | Mostly symbolic but there are 3 sub-questions that are |
The four representations, that is, Macroscopic, Particulate, Symbolic, and Graphic, were used to examine Julien’s teaching of the kinetic molecular theory, Boyle’s Law and Charles’ Law. Classroom instruction techniques such as experiments, demonstrations, activities, assignments and summative assessments were examined to determine the types of representations used for the specific student action.

**Macroscopic Representation.**

Julien uses the macroscopic representations to teach the kinetic molecular theory, Boyle’s Law and Charles’ Law. When teaching the kinetic molecular theory, Julien uses latex balloons as examples. He focuses class discussions about what keeps balloons inflated. In teaching Boyle’s Law, Julien has his students conduct an experiment using a certain volume of air trapped in a syringe. Books are added to the top of the plunger in the syringe to act as a proxy for pressure. Students readily observe the decrease in volume of the air trapped in the syringe as more books are added to the plunger.

When teaching Charles’ Law, Julien uses a number of macroscopic representations to teach the relationship between volume and temperature. One of his macroscopic
representations is to have students put dry ice pellets into latex balloons. As the dry ice
warms, the balloon inflates. Keeping that experiment in mind, Julien also uses the examples
of an inflated balloon in a freezer and a warm oven. Julien reports that his students already
seem to know that the balloon in the freezer will get smaller in size and that the balloon in a
warm oven will increase in size. Julien does not demonstrate the balloon in a freezer and
warm oven in his classroom.

Another macroscopic example employed in Julien’s classroom is sealed copper balls
with pressure gauges attached to them. Julien places the copper balls in different temperature
water baths and has students collect temperature and pressure data. Even though this
experiment focuses on the relationship between temperature and pressure, which is not
Charles’ Law, Julien uses this macroscopic example of the relationship between temperature
and pressure to help students understand the relationship between temperature and volume,

They [students] seem to have enough understanding so we try to develop that the
relationship is directly proportional so if a Kelvin temperature is doubled, what would
expect… and so on. And then when we talk about the pressure and temperature that
we help them, we go back and help them reinforce the volume and temperature
relationship.

Particulate Representation.

When talking about what keeps a latex balloon inflated using either air or dry ice,
Julien furthers his macroscopic representation by talking about the air particles inside the
balloon. He talks about the parts of the kinetic molecular theory; particles are in constant,
rapid, random motion, the particles of gas are very small, and the distance between the
particles is very large. Julien has developed hand signals that correspond to each part of the
theory and uses them repeatedly in class when discussing particles. Julien reports that after a
time, he does not need to say the words of the theory but just produce the hand signals and
students will recite the words for him.

Another example of Julien’s use of the particulate representation occurs during the
Boyle’s law lab using the syringe and books: two analysis questions that focus on the air
particles trapped in the syringe. The first question asks students to describe what is
happening to the air particles in the syringe as the plunger increases pressure. The second
question asks students to explain “on an atomic level, why it would be impossible to achieve
a volume of 0.0 mL for the gas trapped in the syringe”.

A third example of the particulate representation is found during the experiment with
the copper balls in different temperature water baths where the data and graph drawn are
used to find absolute zero. Julien says,

Its kind of a jumping off point to reinforce this idea of Kelvin or an absolute
temperature scale. We talk about the particles, you don’t see them of course, what are
the particles now doing? And in dry ice and alcohol, what are the particles doing? (he
speaks very slowly to illustrate reduced speed of the particles).

One of Julien’s favorite assignments for his students during the Gas Laws unit is
another example that uses the particulate representation. This assignment is found in the
textbook. An analogy is set using dancers, who represent gas particles, on a dance floor,
which represents volume. Students are asked to determine what the tempo of the music, the
size of the dance floor, and the frequency of collisions between dancers represent. Upon
identification of the variables, students are then asked to determine what will happen to the
other variables if one of the variables is changed. For example, if the dance floor (volume) is
suddenly doubled, what will happen to the number of collisions (pressure) between the dancers?

*Symbolic Representation.*

Julien uses the symbolic representations occasionally. Julien has students work through typical problems using Boyle’s and Charles’ Law as a part of the experiment with the syringe and books. However, students do not do calculations on the data they have collected. The traditional symbolic word problems students do are devoid of context. Julien also has students do calculation problems at the end of the section on gases in a section summary from the textbook. Julien does not have students do conversions of units of measurement for pressure, volume or temperature for any of the problems given as assignments.

*Graphic Representation.*

Julien uses the graphic representation twice in his Gas Laws Curriculum. For the two experiments that Julien has students conduct, the syringe and books lab to illustrate Boyle’s Law and the copper ball in different temperature water baths to show the relationship between pressure and temperature, which Julien incorrectly calls Charles’ Law; Julien has students graph their data. Julien reports, “We do a simple graph and that helps them see that relationship also.” In addition to showing relationships between variables, the graph drawn for the incorrectly named Charles’ Law is also used to find absolute zero through extrapolation of the experiment data,

When they graph and extrapolate back, they see where \(-273[^\text{degrees Kelvin}]\) is and, and, and the, its kind of a jumping off point to reinforce this idea of Kelvin or an absolute temperature scale.
Student Conceptions in Teaching Practice

The first scenario (See Appendix B) is a sealed Erlenmeyer flask that is filled with air. An evacuation pump is connected to the flange in the flask and some of the air is pumped out. The pump is removed from the flange. Participants were asked to draw what they thought their students would draw about the air particles in the flask after some of the air had been removed. Julien readily predicted that his students would draw the air molecules as dots on the bottom of the flask, as if they had sunk.

Figure 4.9: Julien’s Drawing of Student Conceptions for the First Scenario of the Written Assessment

Driver’s (1985) Children’s Ideas of Science, Nussbaum (1985), and Lin et al (2000), report that drawing the air particles on the bottom of the flask is a common alternate conception. Julien did not provide additional alternate conceptions.

When questioned about how he would address this alternate conception in his teaching, Julien responded that he would show the students the correct answer. He would then use the hand motions that he has developed for the parts of the kinetic molecular theory to help his students think about the particles in the flask. Julien also gave an example of
having the students think about the air in the room. Julien would ask his students “Is the air all on the bottom of the floor?” Julien would reply, “No. Air is all around the room equally filling the room. Just like the air in the flask.”

The second scenario (See Appendix B) showed a cross-section of a steel tank full of hydrogen gas. The hydrogen molecules are drawn as dots in the tank. Again, participants were asked to predict what they think their students will show of the cross-section when the tank is cooled. Julien thought that his students would draw the molecules on the bottom of the tank.

*Figure 4.10: Julien’s Drawing of Student Conceptions for the Second Scenario of the Written Assessment*

On the *Chemical Concepts Inventory*, this is one of the alternate conceptions given.

Julien mentioned a number of strategies to address this alternate conception. First Julien stated that reminding students of the parts of the kinetic molecular theory, and using his hand motions, to explain what is happening to the particles in the steel tank. A second teaching strategy was to think about the air in the classroom. Julien would ask his students, “If the windows are opened and it gets cold in the classroom, are the oxygen molecules going to sink to the floor?” Another possible strategy Julien proposed was to show the students the correct answer and talk through why it is correct. Julien’s final example of how he might address students’ alternate conceptions would be to use the idea of a liquid taking the shape of its container and talking about the properties of liquids.
Case Three: Matthew

Background

Matthew teaches at a private, Catholic, single-sex, suburban school in a large metropolitan area in the Midwest. St. Dominic’s High School enrolls approximately 700 students, grades 7-12, focusing on preparing students for college. Last school term, 98% of graduating seniors went on to post-secondary education. Students come from a large area surrounding the school, including a nearby state. Most students at St. Dominic’s are children of white, affluent parents; only 30% of students receive some financial assistance for tuition. Three years of “Lab science” are required to graduate—physical science, biology and chemistry. Chemistry is typically taken in the junior year. Similar to Julien’s school, Matthew’s school offers two levels of chemistry: general chemistry and Honors chemistry. Class sizes average 22 students for science classes.

Matthew earned a bachelor’s of science in chemistry and then completed the same post-baccalaureate program as did Erik and Julien, earning his master’s degree in science education. Matthew has finished his fourth year of teaching at St. Dominic’s. Each year he has written and re-written his own curriculum for his chemistry and physical science courses, improving the program each year, he feels, and discarding what he no longer finds useful. Because his colleague does not want Matthew to duplicate in his ninth grade physical science course any of the experiments she uses in her chemistry course, Matthew spends a lot of time in a somewhat frustrating search for novel experiments.

Matthew has been using a mass-marketed traditional textbook for the last four years in his chemistry course. He finds that the text for his general chemistry students is very mathematics heavy. A new textbook was chosen for the new school year that focuses
primarily on inquiry and conceptual understanding of chemical concepts. Matthew is very excited about the new text and is looking forward to the next school term. For the present study, the curriculum Matthew has been using during the last four years was investigated.

Subject Matter Knowledge for Teaching the Gas Laws

During the first interview, Matthew was asked to respond to three scenarios featuring the kinetic molecular theory, Boyle’s Law and Charles’ Law (See Appendix B). Each of Matthew’s responses was scored using a rubric developed for this study. The following table shows Matthew’s scores.

<table>
<thead>
<tr>
<th>Item</th>
<th>Score</th>
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<th>Targeted Representation</th>
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<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>1b</td>
<td>2</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2a</td>
<td>3</td>
<td>Identifying pressure/volume differences</td>
<td>Macroscopic</td>
</tr>
<tr>
<td>2b</td>
<td>2</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2c &amp; 2d</td>
<td>1</td>
<td>Applying Boyle’s Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>2e</td>
<td>0</td>
<td>Applying Boyle’s Law</td>
<td>Graphic</td>
</tr>
<tr>
<td>3a</td>
<td>3</td>
<td>Predicting gas/volume changes</td>
<td>Macroscopic</td>
</tr>
<tr>
<td>3b</td>
<td>1</td>
<td>Applying Charles’ Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>3c &amp; 3d</td>
<td>2</td>
<td>Applying Charles’ Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>3e</td>
<td>0</td>
<td>Applying Charles’ Law</td>
<td>Graphic</td>
</tr>
</tbody>
</table>

Kinetic Molecular Theory -- Question 1a:

Question 1a focused on the assumptions of the kinetic molecular theory and the accuracy of drawing gas molecules within a closed container. Matthew chose to draw his response and to explain his thinking for this question (See Figure 4.11 below).
As he drew, Matthew stated,

\[
\text{CO}_2 \text{ and O}_2 \text{ will have the same average kinetic energy but the oxygen will be lighter, which mean will be a little faster. Let’s see, and they [CO}_2 \text{ and O}_2 \text{ molecules] should be equally distributed, both of them in the flask. Now, I’m going to try and draw that.}
\]

In the drawing, Matthew has equal numbers of oxygen and carbon dioxide molecules shown in random motion with lines coming out from the molecules to indicate motion. There is an even distribution of molecules in the flask. Matthew has drawn oxygen as diatomic and the carbon dioxide as linear with a larger carbon atom in the center of the molecules and smaller oxygen atoms on either side of the carbon atom. Matthew comments that both gases have the same average kinetic energy even though the “oxygen molecules will be lighter, they will need to be a little faster” to equal the average kinetic energy of the heavier carbon dioxide molecules which are moving more slowly. While the masses and velocities of the molecules are different from one another, this is not part of the ideal response.

\textit{Kinetic Molecular Theory--Question 1b:}

Question 1b focused on the assumptions of the kinetic molecular theory and the accuracy of drawing gas molecules within a closed container, now, however, with the
variable of heat added to the scenario. Matthew drew his conception of oxygen and carbon
dioxide being heated in the flask (See Figure 4.12).

Well, we’re going to move it faster. That’s the only difference I’m seeing here,
pressure would increase but that shouldn’t matter for the most of the particles, so
more collisions and stuff. … They’re moving faster because as the energy increases
in the system so the more kinetic energy, so they’re both moving faster, oxygen
should be moving on average faster than the CO₂ again.…

*Figure 4.12: Matthew’s Drawing for Question 1b of the Written Assessment*

Matthew drew eight diatomic oxygen molecules and eight linear carbon dioxide molecules
randomly scattered through out the flask. This drawing is very similar to the drawing
Matthew drew for question 1a. As Matthew explained this drawing he stated,

Yes, pressure will increase because the temperature was increased and the volume
stays the same, so we’re going to have more collisions… the more and greater
pressure.
While Matthew exhibits the majority of components of the kinetic molecular theory in his drawings and explanations, he does not mention that there are no interactions between particles and that the volume of the gas particles is assumed to be zero.

Identifying Pressure and Volume Differences—Question 2a and Kinetic Molecular Theory—

Question 2b:

These questions focused on the ability of the participants to identify pressure and volume differences and explain their response for a novel situation (See Appendix B, 2a). Matthew correctly predicts that the level of oil in the glass tube of the apparatus will increase, thus decreasing the volume of air trapped in the glass tube. “Okay, so if I understand this right, air comes in here into the reservoir and pushes the oil down, which is then pushed up on the other side, which would increase the length of the oil in the glass tube.” As Matthew explains his reasoning,

Okay, so I’m assuming like this is sealed off and we have some pressure--the air inside the reservoir and the glass tube. Okay, the pressure of the air on the right side, in the reservoir, versus on the left side should be equal, which is how you get your height of your column. Per my belief at the moment, when you add pressure into the right, that increased pressure will push back at the trapped air and so, that volume of oil will be pushed down and up the left side, so the column of oil will increase. And because it increases, it’ll stop when the trapped air’s pressure now equals the pressure that you pumped in.

Matthew’s response to the question does not address the particulate representation but rather the macroscopic. Matthew focuses on the pressure in the reservoir and on the trapped gas in the glass tube. He focused on pressure having to be equal in the reservoir and glass tube in
the apparatus before and after additional air is added to the system. He does not mention the particulate representation of the air molecules in the reservoir or glass tube. He does not mention the particulate representation of how pressure is increased—by additional air molecules being introduced into the system or increased collisions between molecules.

*Applying Boyle’s Law—Question 2c and 2d*

These questions asked participants to determine what data should be collected and how to collect data for volume in the glass tube for any given pressure. In answering the general question 2c about what data he would collect for volume in the glass tube for any given pressure, Matthew responded,

The temperature would need to be known. So, we need to know pressure. Oh, that’s not the question, sorry. We’re trying to compare any given pressure. We need to know the temperature, trying to find volume. Number of moles won’t change. That really shouldn’t matter, assuming this is ... We need air, not the oil. But I’m trying to find the real weight of the matter. That shouldn’t matter I think. When you do atmospheric pressure, we’re not worried about the moles in the atmosphere so that won’t change.

Matthew gets very confused at this point. He is not sure what he is trying to find in the given question. Eventually, the conversation returns to the question about determining the volume in the glass tube for any given pressure. Once Matthew is focused on the question again, he responds, “Oh, I think if I know the initial pressure and volume, I can just do a change, so the mole shouldn’t matter.”

Eventually, Matthew’s response is similar to the ideal response. Matthew mentions knowing the pressure in the reservoir before and after air is added as well as knowing the
initial volume of gas in the glass tube. Knowing those three variables, Matthew states, “Using the combined gas law or whatever [other gas law equation] that’s causing the temperature is, supposedly Charles, I believe.” Matthew also takes into account that temperature of the system must be constant as well as the number of moles in the atmosphere.

In answering question 2d, Matthew seems more certain about his responses. He states,

So, I have my pressure gauge. I can record the temperature of the system with the thermometer, and that’s all I’m saying I need. And I can read the volume on the left side, so I should get a set.

Matthew is confident about reading the pressure gauge and scale for volume of the trapped gas. Again, Matthew mentions temperature. However, he wants to measure the temperature of the system with a thermometer. He does not assume that the temperature will remain constant. This is curious in this case. It would seem that because Matthew teaches that Boyle’s and Charles’ Laws are special cases of the Combined Gas law Matthew constantly thinks about the three variables of pressure, temperature and volume in the Combined Gas Law interacting for any given scenario, regardless of whether or not the scenario warrants it.

*Applying Boyle’s Law--Question 2e*

This question asked participants to graph the data that they would have collected from the previous question. In response to being asked to graph the data he might collect from question 2d, Matthew said,

Do I graph the inverse of it, I believe? We did that in Physical Science here. You have to graph the inverse. The temperature would need to be in Kelvin if I’m to graph it but it doesn’t matter, it’s constant. Alright, so if I graph the inverse of – see,
now I’m thinking why we did this here and the graph of the inverse is linear. If you don't graph the inverse, it’s one of these deals (drawing a power-inverse curve). Matthew is the only participant who graphed the inverse of volume vs. pressure. He seemed to prefer the linear inverse graph to the power-inverse graph (See Figure 4.13). Matthew reports that he has his students draw both graphs but he seems much more comfortable with the linear inverse graph.

*Figure 4.13: Matthew’s Graph for Question 2e of the Written Assessment*

*Predicting Volume of Gas Changes--Question 3a and Applying Charles’ Law--Question 3b:*

These questions asked participants to predict the direction the oil plug would move in the apparatus and explain their reasoning if the apparatus were to be moved to a colder environment. Matthew correctly predicts that the oil plug will move toward the left when the apparatus is taken to a colder environment. However, Matthew identifies pressure and temperature as the changing variables for the apparatus instead of the correct response of volume and temperature. Matthew said,

Because we’re going to have this [apparatus] going outside, the pressure inside the tube will decrease with the decrease in the temperature and loss in volume so, the way I’m reading this...Because pressure decreases – I’m sorry, because the temperature decreased, pressure will decrease. You’re going to have some of the molecules,
you’re going to have less collisions and so on. That would cause the outside pressure to push the oil drop in [towards the left] further.

*Applying Charles’ Law--Questions 3c & 3d*

These questions asked participants to determine what data should be collected and how to collect data for volume in the apparatus for any given temperature. Participants needed to identify what two variables were changing (volume and temperature), identify the gas law employed (Charles’ Law), and determine what variable was remaining constant (pressure). After they described this in general terms, question 3d asked participants for the specifics of how to determine the volume in the apparatus.

In the previous question, Matthew identified the changing variables for the scenario as temperature and pressure. However, when asked to determine what data to collect and how to collect it, he responded that there is “no relationship directly for the distance the oil drop travels, but, let’s see…”. Matthew does not recognize that the distance the oil drop travels is really a volume measurement. Matthew sees volume as the variable that is remaining constant. However, later in the interview, Matthew states that he would measure the oil drop’s movement as a measurement for pressure,

I suppose I will just do the same kind of deal as before where we’re keeping the volume constant, so we’re just changing pressure and temperature. And so I will just record the changes in the oil drop’s movement, maybe per Kelvin. I’ll be able to predict then at different temperatures where the oil drop would be.

When asked about how he would collect data, Matthew responds with,

I’m going to be in a situation where I can change the temperature as my belief. So, I would… as I change temperatures, I would probably just record the every length of
the tube from where it comes out of the flask to where it meets the oil drop. That would be a corresponding pressure measurements for like the oil was on the other, I’m sorry, the length of column of air. There’s that column changes. It would go down as the pressure outside increased comparatively, so the pressure outside wouldn’t change. As the pressure inside the tube is less then the column will be less, therefore, the oil drop distance. I guess my measurements should simply be temperature of the system and the corresponding distance of my oil drop to the top of the flask where it is stoppered.

Again, Matthew does not see that the distance of the tubing from the top of the flask where it is stoppered to the location of the oil drop is actually volume. He sees the oil drop measurement as a pressure measurement. Matthew gives an example of his thinking, “it’s like the millimeters of Mercury. There’s a column of – from this distance, I guess, the millimeters of the air and that—whatever this is; is this a vacuum tube, whatever is out here.” Matthew does not recognize that pressure is the variable held constant in this scenario even though he recognized that in the previous scenario that pressure in the reservoir and glass tube would have to be equal. He does not apply that information to this current scenario.

*Applying Charles’ Law--Question 3e:*

This question asked participants to graph the data that they would have collected from the previous question. Matthew responds correctly regarding the shape of the graph, positive increasing linear line.
However, Matthew graphs pressure as a function of temperature. Again, Matthew is focused on the variables of temperature and pressure instead of the correct response of temperature and volume. Regardless of the variables graphed, he is certain that the resulting graph should be linear.

It would be a linear graph. Let’s see, it should be something with-- independent dependent variables, like that I guess. Alright. So as we’re changing temperature, what happens to pressure? As the temperature goes up, the pressure goes up. I hope in the graph I drew you as the right thing there. I just drew you a linear graph, I don't know if I paid attention to what was what.

Pedagogical Content Knowledge

Pedagogical Content Knowledge was assessed through two avenues in this study. The first avenue was to ask the participants if they would use in their own classrooms the apparatus presented in the first interview. Follow up questions asked how and why the apparatus would be used or not used. This line of questioning gave participants the opportunity to talk about their PCK in relation to the novel apparatus, thus demonstrating their understanding of the subject matter knowledge for teaching underlying the concepts for which the apparatus can be used, their pedagogical knowledge regarding the use of the apparatus, and their knowledge about learners in how the participants would present the
apparatus and what they students would be asked to do with the apparatus. Here, the
dynamic nature of PCK can be seen and, perhaps, documented.

The second avenue of assessing PCK was to ask the participants how they actually
teach their unit on the Gas Laws. This information was obtained in the second interview.
Participants were asked to provide lecture notes, worksheets, experiments and assessments in
addition to describing in detail how they teach their Gas Law unit. By discussing their
practice and displaying artifacts, participants were able to talk through their thinking and
decision making process that forms the foundation of lesson planning and execution.

These two methods of assessing PCK, discussion about the possible use of new
apparatus and descriptions of actual classroom practice, illuminate the participants’ use of
representations and their understanding of student conceptions.

*Use of Apparatus Presented in Scenarios*

Regarding the first apparatus, the oil reservoir and glass tube where air is added to the
reservoir (See Appendix B), Matthew said he would use the apparatus in his classroom as an
experiment for small lab groups of two or three students. Matthew said he would have his
students “just start comparing pressures and read corresponding volumes and I had to see if
they could—for them, I’d see if they could find a relationship” between the pressure and
volume variables. Matthew continues to outline a complete lesson for the apparatus. He
says,

And I would recommend – again, I need to guide them to graph, I’ll do a graph but I
will always ask them to try and graph the data. I was thinking I can do a large graph
where they can I put the data together as one big group data. And I can have a large
graph collecting more data points, which is where I talk about the issue of different
instruments in the error. The error in reading them versus different people reading them. This has been our discussion...

When describing the objective(s) for the lesson, Matthew states,

I probably would want them to take home the relationship of Boyle’s Law. And understand that equation, the at constant temperatures, pressure increases, what happens to volume, and that there’s a linear relationship [between pressure and volume].

What is interesting about Matthew’s comments is that he is the only participant to describe a lesson beyond collecting data to illustrate that as pressure increases, volume decreases. In Matthew’s lesson, he describes how he would have his students graph their data, make a large class graph and discuss relationships as well as sources of error. Matthew’s PCK is made evident by his use of the apparatus to illustrate the macroscopic representation of pressure increases as the cause of volume decreases. He then goes to the graphic representation to show the relationship between pressure and volume. While Matthew does not mention explicitly the symbolic representation of Boyle’s Law in his lesson description, he does mention the equation of Boyle’s Law as an objective for the lesson.

Asked about possible classroom use of the second apparatus, the Erlenmeyer flask and tubing with the oil plug where the apparatus is moved from different temperature environments, Matthew said he probably would not use this apparatus in his classroom.

There are three laws. I don't know if I’d investigate all three of these because at a time, I don't know if I’d be investigating Boyle’s, Gay-Lussac’s and Charles’. I don't know if I’d get most of the three. The interest and see how students get around in
trying to measure this bended tube. Just, time-wise, I like the other one [the first scenario with the oil reservoir and trapped gas in the glass tube] better, that's all.

Matthew does not see the Erlenmeyer flask with oil plug scenario as an example of Charles’ Law. He sees the apparatus as a combination of gas laws and does not teach all three of those laws separately in his curriculum. Matthew focuses on the Combined Gas Law and then teaches only Boyle’s and Charles’ Laws as special cases of the Combined Gas Law.

This apparatus is being rejected based on its inability, in Matthew’s view, to represent the gas laws that he teaches. Matthew also was concerned about the execution of the experiment based on the temperature. He was not sure how he would go about changing the temperature of the environment in which the apparatus would be placed. Matthew’s PCK is focused on the execution of the experiment and his uncertainty about the apparatus illustrating the gas laws of his curriculum.

*Representations in Teaching Practice*

In order to understand the representations used by Matthew in his teaching practice, it is necessary to understand how he teaches his unit on Gas Laws. The following table outlines Matthew’s curriculum in brief along with the representations focused on during each activity.

*Table 4.6: Matthew’s Curriculum of Gas Laws Unit*

<table>
<thead>
<tr>
<th>Day 1</th>
<th>Curriculum</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>KMT</td>
<td>1. Prior Knowledge-what do kids know about gases&lt;br&gt;2. 5 statements in text and discuss differences&lt;br&gt;3. Ideal vs. Real discussed as part of 5 statements&lt;br&gt;4. Expansion of gases based on 5 statements&lt;br&gt;5. Homework from text</td>
<td>1-5: Particulate</td>
</tr>
<tr>
<td>Day</td>
<td>Activity</td>
<td>Representation</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Day 2</td>
<td>1. Lab-Pop Can crushing in pairs</td>
<td>1. Macroscopic</td>
</tr>
<tr>
<td>Day 3</td>
<td>Combined Gas Law</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Lecture showing Boyle and Charles Law</td>
<td>1. Symbolic</td>
</tr>
<tr>
<td></td>
<td>2. Practice Problems (3 days of problems)</td>
<td>2. Symbolic</td>
</tr>
<tr>
<td></td>
<td>3. Demo-marshmallow in syringe</td>
<td>3. Macroscopic</td>
</tr>
<tr>
<td></td>
<td>4. Demo-Boil water in syringe</td>
<td>4. Macroscopic</td>
</tr>
<tr>
<td>Day 4</td>
<td>Grahams Law of Diffusion</td>
<td>1-2 Symbolic</td>
</tr>
<tr>
<td></td>
<td>1. Lecture showing equation and how to manipulate it.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Lecture showing KE equation</td>
<td></td>
</tr>
<tr>
<td>Day 5</td>
<td>Graham's Law of Diffusion</td>
<td>Macroscopic with Symbolic Questions</td>
</tr>
<tr>
<td></td>
<td>Lab-HCl/NH₃ diffusion</td>
<td></td>
</tr>
<tr>
<td>Day 6</td>
<td>Review with Review Packet</td>
<td>Symbolic</td>
</tr>
<tr>
<td>Day 7</td>
<td>Test</td>
<td>4 problems--symbolic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 essay about KMT--particulate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10-15 Multiple choice—symbolic, particulate and macroscopic</td>
</tr>
<tr>
<td>Day 8</td>
<td>Stoichiometry</td>
<td></td>
</tr>
<tr>
<td>Day 9</td>
<td>Stoichiometry</td>
<td></td>
</tr>
<tr>
<td>Day 10</td>
<td>Stoichiometry</td>
<td></td>
</tr>
<tr>
<td>Day 11</td>
<td>Standard Temperature and Pressure as it relates to gases. Taught with stoichioimetry and lots of unit conversions</td>
<td>Symbolic</td>
</tr>
<tr>
<td>Day 12</td>
<td>Ideal Gas Law</td>
<td>Symbolic</td>
</tr>
<tr>
<td></td>
<td>PV=nRRT as it relates to Combined Gas Law</td>
<td></td>
</tr>
<tr>
<td>Day 13</td>
<td>Lab-Find R in the Ideal Gas Law</td>
<td>Symbolic and Macroscopic</td>
</tr>
<tr>
<td>Day 14</td>
<td>Quiz</td>
<td>Symbolic</td>
</tr>
<tr>
<td>Day 15</td>
<td>Airbag Lab</td>
<td>Macroscopic and Symbolic</td>
</tr>
<tr>
<td>Day 16</td>
<td>Review Packet</td>
<td>Symbolic</td>
</tr>
<tr>
<td>Day 17</td>
<td>Test</td>
<td>All problems--Symbolic</td>
</tr>
</tbody>
</table>
The four representations, that is, Macroscopic, Particulate, Symbolic, and Graphic, were used to examine Matthews’s teaching of the kinetic molecular theory, Boyle’s Law and Charles’ Law. Classroom instruction techniques such as experiments, demonstrations, activities, assignments and summative assessments were examined to determine the types of representations used for the specific student action.

**Macroscopic Representation.**

Matthew does use the macroscopic representation to teach Boyle’s Law and Charles’ Law. When teaching Boyle’s Law, Matthew uses a demonstration. He places a large marshmallow into a very large syringe. When the plunger is pushed into the syringe (increasing pressure inside the syringe) the marshmallow decreases in size (decreasing volume of gas bubbles in marshmallow). When the plunger is pulled in the opposite direction, the pressure is decreased in the syringe, which allows the gas bubbles in the marshmallows to expand, increasing in volume, and the marshmallow increases in size.

When asked about his teaching of Charles’ Law, Matthew describes a demonstration where he puts some warm water into a very large syringe.

There’s one more syringe thing to do, which is just putting in some warm tap water.

And then having pretty much no air in there and I pull back the syringe and it boils at room temperature.

Matthew intends to state that the water will “boil” as the pressure is increased by the plunger in the syringe. Matthew mistakes Charles’ Law, the relationship between volume and temperature, for the relationship of pressure and temperature. In the demonstration, Matthew focuses on how the pressure is changing in the syringe instead of focusing on volume and
temperature for Charles’ Law. Matthew repeatedly makes this error throughout the interview.

Particulate Representation.

When beginning the unit on gases, Matthew first asks students what they know about gases. Upon soliciting his students’ prior knowledge, Matthew refers to his textbook. In the beginning of the chapter on States of Matter but which Matthew uses at the beginning of his unit on gases, a small section entitled Kinetic Molecular Theory lists five statements about the behavior and properties of gases. He then uses the five statements from the text to wed students’ prior knowledge to the kinetic molecular theory. During this instruction, Matthew uses the particulate representation. This is the only time Matthew uses the particulate representation during his instruction of his unit on gas properties and behavior.

Symbolic Representation.

The symbolic representations are used often in Matthew’s instruction. Matthew starts his instruction with the Combined Gas Law to illustrate how Charles’ Law and Boyle’s Law are special cases of the Combined Gas Law. Matthew does this through mathematical manipulation. There are a number of assignments, worksheets, and problems from the text and review packet focusing on the mathematical manipulation of the formulas. For example, Figure 4.15 below.

*Figure 4.15: Example of a Symbolic Question Used by Matthew.*

1) A chemical reaction produced 23.4 L of carbon monoxide gas, CO, at STP. What was the mass of the gas produced?

These types of problems are routinely assigned and students are expected to work through them. Matthew focuses mostly on the symbolic representation during his instruction of gases.
Graphic Representation.

Matthew seems to use the graphic representation during his instruction of gases only in conjunction with the laboratory experiment for Boyle’s Law. The experiment that illustrates Boyle’s Law is a syringe with books stacked on top of the plunger. Students measure the volume of gas inside the syringe and use the books as a proxy for pressure. Matthew has students graph pressure as a function of volume, and graph pressure as a function of the inverse of volume. During the interview, Matthew focused on the inverse of volume as a function of pressure. The focus of Matthew’s conversation was the direct relationship of the inverse volume as a function of pressure.

Student Conceptions in Teaching Practice

The first scenario (See Appendix B) is a sealed Erlenmeyer flask that is filled with air. An evacuation pump is connected to the flange in the flask and some of the air is pumped out. The pump is removed from the flange. Participants were asked to draw what they thought their students would draw to illustrate the air particles in the flask after some of the air had been removed. Matthew predicted a number of student conceptions that he might see in the drawing, for example, that students might draw nothing—that the flask is empty, or might draw more air molecules. He also mentioned that most of his students would draw the correct model. When pushed, Matthew did mention a student conception consistent with the literature,

There might be, you know, maybe they only had taken – you know like halfway, like they actually only... wherever that nozzle is. I think above that line would kind of go out, and anything below, would still stay there.
Matthew also predicted that his students would draw the air molecules as dots on the bottom of the flask, as if they had sunk. Driver’s (1995), Children’s Ideas of Science, Nussbaum (1985), as well as Lin et al (2000), report that drawing the air particles on the bottom of the flask is a common alternate conception.

When questioned about how he would address this alternate conception in his teaching, Matthew responded that he would talk about the correct answer to his students. He would remind his students about the behaviors of gases, such as,

There’s probably a gas that is always moving, you know, indefinite shape and volume, so it [the gas] should be filling this container. So, when this nozzle is open, some of the gas is going to go out. It’s [the gas molecules are] all random and moving, so there’s no reason why it [the gas molecules] wouldn’t leave from all areas of the flask. It [the gas molecules] goes towards that hole like there’s – the force, it’s being forced out. And that, it [the gas molecules] would still occupy—it will fill up the rest of the container after all of the—whatever is left. It would fill up the container and it will be randomly distributed in there.

Matthew also said that he would “try to let them use anything to actually demo it--but let me think. Not much I said—I’m going to try everything like having the kids stay in a confined area.” Matthew went on to explain his idea,

Like even take, like rope, and like section off student desks where in a small area. Students would really move close together. And then if you tell half of them [the students] to get out, they’re going to actually spread out to the rest of the area.

Matthew is the only participant who mentioned having students act out the behavior of gas particles. In having students act out what is happening to the gas particles in the flask,
Matthew’s PCK is engaged. However, Matthew’s understanding of student conceptions is limited. He believed that almost all of his students would draw the correct answer. However, Nussbaum (1985) and Lin et al (2000) show that a large percentage of students do have alternate conceptions regarding the behavior of gases. Matthew does not seem to have a solid grasp of student conceptions beyond the “right answer”.

The second scenario (See Appendix B) showed a cross-section of a steel tank full of hydrogen gas. The hydrogen molecules are drawn as dots in the tank. Again, participants were asked to predict what they think their students will show of the cross-section when the tank is cooled. Matthew was not able to identify alternate student conceptions beyond students perhaps drawing particles in the liquid or solid state (See Figure 4.16),

*Figure 4.16: Matthew’s Drawing of Student Conceptions for the Second Scenario of the Written Assessment.*

I don't see a lot of them drawing it different. Some might start solid. Some of the hydrogen maybe in the liquid state, but it doesn’t say how low [the temperature] is getting in the question. You always have, you know, the distribution of temperature. The kinetic energy of molecules are going to be in that state, just like you only have water vapor and you have liquid water in the room. I can't really think of anything that I will be doing that would stick out to me right now as being horribly wrong.

Matthew does not present an alternate student conception to this scenario. He does speak of the problem of not knowing how much the temperature would be lowered. Matthew offered
that the hydrogen gas might be cold enough to be in the solid or liquid state. Thus, any drawing of clustered molecules in the tank may be valid.

Because Matthew did not present any student alternate conceptions, he did not mention any strategies to address any alternate conceptions. He did point out though that the lack of explicit information regarding the new lower temperature of the tank, as well as the boiling and melting points of hydrogen, would be a problem for him and very likely for his students.

Case Four: Sam

*Background*

Sam has been teaching for forty years. The first ten were in a rural area of a Midwest state. The last thirty have been at a private, Catholic, college-preparatory day and boarding school in a smaller metropolitan area in the Midwest. St. Peregrine’s Middle and Upper School enrolls approximately 345 students in grades 7 – 12. Students come from all over the United States as well as 16 foreign countries. Nearly 100% of graduates attend post-secondary education institutions. St. Peregrine’s requires three years of science for graduation—physics in the ninth grade, chemistry in the sophomore year and biology in the junior year. Many students take at least one science elective course during their senior year.

There are two levels of chemistry offered at St. Peregrine’s. The first level, chemistry, is required during the sophomore year. Advanced chemistry was introduced twenty years ago as an elective course that focuses on organic chemistry and biochemistry, typically taken during the junior or senior year. Sam is the only chemistry teacher at St. Peregrine’s and so teaches both chemistry and advanced chemistry. Because lab space is
limited in Sam’s classroom, class sizes tend to be around 15 – 18 students for each level of chemistry. For this study, Sam’s required chemistry course was investigated.

This past school year, the sequence of science courses was changed to move physics to the ninth grade. Thus, this year’s ninth grade students will take chemistry as sophomores. Sam has not taught sophomores in at least twenty years and so is curious to see what class will be like next year, but he is more interested in how the students will deal with the math of chemistry after having had physics first. Sam thinks that typical junior chemistry students do not understand how to apply mathematics to science concepts. He is hoping that experience gained in the ninth grade physics classes, that is, applying mathematical relationships to data collected in experiments, will make the use of math to understand chemistry concepts easier for most students.

Sam has been developing his chemistry curriculum for forty years. The text he uses is traditional and mass-marketed. He keeps a box full of worksheets, overhead transparencies, and experiments of the curriculum he has collected since he began teaching. When planning, Sam goes through the box and pulls out what he likes or seemed to work well last year.

Subject Matter Knowledge for Teaching the Gas Laws

During the first interview, Sam was asked to respond to three scenarios featuring the kinetic molecular theory, Boyle’s Law and Charles’ Law (See Appendix B). Each of Sam’s responses was scored using a rubric developed for this study. The following table shows Sam’s scores.
Table 4.7 Sam’s Subject Matter Knowledge for Teaching Assessment Scores

<table>
<thead>
<tr>
<th>Item</th>
<th>Score</th>
<th>Chemistry Concept</th>
<th>Targeted Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>2</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>1b</td>
<td>3</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2a</td>
<td>3</td>
<td>Identifying pressure/volume</td>
<td>Macroscopic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>differences</td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td>1</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2c &amp; 2d</td>
<td>2</td>
<td>Applying Boyle’s Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>2e</td>
<td>2</td>
<td>Applying Boyle’s Law</td>
<td>Graphic</td>
</tr>
<tr>
<td>3a</td>
<td>3</td>
<td>Predicting gas/volume changes</td>
<td>Macroscopic</td>
</tr>
<tr>
<td>3b</td>
<td>2</td>
<td>Applying Charles’ Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>3c &amp; 3d</td>
<td>2</td>
<td>Applying Charles’ Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>3e</td>
<td>3</td>
<td>Applying Charles’ Law</td>
<td>Graphic</td>
</tr>
</tbody>
</table>

Kinetic Molecular Theory--Question 1a:

Question 1a focused on the assumptions of the kinetic molecular theory and the accuracy of drawing gas molecules within a closed container. Sam did not draw a picture. He verbally explained,

Moles and volume would be the same, but the masses would be different. In the motion of the particles would be basically a random motion. And based upon gravity, they have your molecule and carbon dioxide would tend to be attracted by gravity more and they collect more in the bottom, even though there would be diffusion of the gases. And you have oxygen and carbon dioxide spread throughout, that the greater concentration would probably be at the heavy one at the bottom, at first. And as diffusion occurred, they would start to even out because of the motion of the molecules.

Sam’s response is correct in that the molecules are in constant random motion and that diffusion would occur between the two gases. However, Sam introduces the concept of gravity acting upon the masses of the molecules in such a way that the “heavier” molecules,
the CO$_2$ would congregate in the bottom of the flask. Sam, as well as Matthew in Case Three, mentions that the “heavier” or “lighter” molecules will be different from one another. The concept of weight of the molecules, however, is not a part of the ideal response.

*Kinetic Molecular Theory--Question 1b:*

Question 1b focused on the assumptions of the kinetic molecular theory and the accuracy of drawing gas molecules within a closed container, now, however, with the variable of heat added to the scenario. Sam explains his conception of oxygen and carbon dioxide being heated,

Well, with the increase of heat, the molecules would move faster and have more kinetic energy. There’d be more pressure, if you were measuring pressure, and depending upon how tightly [the flask] was stoppered, the stopper might come out and how much heat you were adding to it. And the mixing of the two gases or the diffusion of the two gases would increase because of their increased speed or kinetic energy. Of course, both of them would have more pressure because of the increased motion, since the volume would be the same—the overall pressure of the gases inside would increase.

While Sam exhibits the majority of components of the kinetic molecular theory in his drawings and explanations, he does not mention that there are no interactions between particles and that the volume of the gas particles is assumed to be zero. However, Sam does correctly apply Gay-Lussac’s Law to the scenario in that if volume is kept constant, an increase in temperature will cause an increase in pressure.
Identifying Pressure and Volume Differences--Question 2a and Kinetic Molecular Theory—

Question 2b:

These questions focused on the ability of the participants to identify pressure and volume differences and explain their response for a novel situation (See Appendix B, 2a). Sam correctly predicts an increase in the level of oil in the glass tube of the apparatus,

This is a trapped gas. So to increase the pressure, the volume of the gas is going to decrease and the pressure of the gas inside the tube will also increase. So the level of the oil move up in the glass tube and the rest of the oil in the reservoir forward down from the pressure put on it by the added air. And then the pressure itself is going to be greater in the reservoir because of the surface area.

Sam correctly identifies the macroscopic representation. However, he does not address the particles of air trapped in the glass tube. Sam is focused on the air being added to the reservoir that will increase pressure. What is also interesting is that Sam sees pressure in a “physics” light. In physics, pressure is the amount of force over surface area, while in chemistry pressure is the frequency of collisions between particles. Sam talks like a physicist, about pressure increasing because of additional surface area of the oil in the reservoir; not like a chemist describing an increased frequency of collisions between air particles due to the addition of more air particles to the system.

Applying Boyle’s Law--Question 2c and 2d

These questions asked participants to determine what data should be collected and how to collect data for volume in the glass tube for any given pressure. In answering the
general question 2c about what data would he collect for volume in the glass tube for any given pressure, Sam responded,

So if you knew the number of moles, the type of gas and the number of grams of gas trapped in the glass tube, and how much pressure was exerted on the reservoir, then be able to translate that pressure to the pressure in the gas. And the increase in pressure would cause a decrease in volume according to Boyle's law. And then you could predict what the movement [of the oil] would be in the glass tube and how small the volume [of the gas trapped] would be in the glass tube with the increased pressure that is happening.

Sam correctly identifies the variables that would change and the gas law being employed. He is able to talk about how the two variables would change in relationship to one another correctly.

In answering question 2d, Sam uses mathematical symbols and vocabulary to explain his response. He states,

Well, I would know by looking at [the scale] what the volume change was and so—now we had—\( V = V'P' \)—that you knew what the initial pressure was and what the pressure changed to and you could figure out what the volume difference [of the gas trapped in the glass tube] is going to be in the glass tube.

Sam is the only participant who used this type of mathematical equation to show the relationship between volume and pressure. Sam mentioned how he instructs his students

\[ V = V'P' \text{ and } V = VP \text{ and then sets the two equations equal to each other to show Boyle’s Law: } V'P' = VP. \]
Applying Boyle’s Law--Question 2e:

This question asked participants to graph the data that they would have collected from in response to the previous question. In response to being asked to graph the data he might collect from question 2d, Sam said,

Okay, if you were plotting the data as the pressure increase then I could end up in hyperbolic curve. And here is the volume, if you increase the pressure – then the volume here is going to decrease according to that exponential curve.

While Sam uses hyperbolic and exponential to mean the same thing, he does correctly describe that the graph to illustrate the relationship between pressure and volume for Boyle’s Law as a power-inverse curve and not a straight line.

Figure 4.17: Sam’s Drawing for Question 2e of the Written Assessment

Predicting Gas Volume Changes--Question 3a and Applying Charles’ Law--Question 3b:

These questions asked participants to predict the direction the oil plug would move in the apparatus, in the event that the apparatus were to be moved to a colder environment, and to explain their reasoning. Sam correctly predicts that the oil plug will move toward the left when the apparatus is taken to a colder environment. However, Sam identifies pressure and temperature as the changing variables for the apparatus instead of the correct response of volume and temperature. Sam said,
Okay, well as you're going to show the effect of Charles’ Law, where the view have a
direct relationship between the temperature and the pressure—I mean, the volume and
the temperature. So if you move it to a cooler situation, then the gas molecules are
going to not have as much kinetic energy, they're not kind of move as much, not
going to create as much pressure. And therefore, the volume is going to decrease and
so you should be able to see the plug move as this total volume of gas here contracts;
and you have less pressure in here, greater pressure on the outside, pushing the plug
towards the Erlenmeyer flask.

Sam correctly identifies Charles’ Law as the law being illustrated by the apparatus. He
initially incorrectly identifies the two variables changing for Charles’ Law, but immediately
corrects his self and does say Charles’ Law has a direct relationship between volume and
temperature. As Sam explains why the oil plug will move to the left, he does not mention
temperature other than the fact that the apparatus has been moved to a cooler environment.
Sam proceeds to talk about how the cooler temperature impacts pressure which causes the
plug to move. Sam changes the two variables that are changing in the scenario back to the
incorrect response he initially corrected at the beginning his response.

*Applying Charles’ Law--Questions 3c and 3d*

These questions asked participants to determine what data should be collected and
how to collect data for volume in the apparatus for any given temperature. When addressing
these questions, Sam states, “And then, if you know the temperatures and you know the
volume, then you can calculate it and measure it and see how close your counting is.” Sam
identified the correct variables of temperature and volume and that those
measurements/values would need to be known. He also mentioned that by using those
values, a missing value could be calculated. However, he does not mention what the equation is or what the relationship between temperature and volume is.

When asked how to collect data to determine where the oil plug will be in the tubing for any given temperature, Sam replied,

And if you do that, of course, if you have enough tubing, the plug’s going to move the other way or just drop out. And if you have a permanent, you know, if you have a sealed end over here – Then the pressure’s going to go up and if you have a device, you know, if you can measure the pressure, you could – In the flask, you could see that the pressure would increase as you went the other way with the temperature. As the molecules are moving faster, creating more pressure, increasing the volume. And so the pressure in the plug is greater on the inside than the outside and move outward— Away from the flask.

Sam was very concerned with assumptions of the apparatus, for example, assuming there was enough tubing, assuming the stopper was completely sealed. However, there seemed to be some confusion about which variable was changing, temperature or pressure, in relationship to volume.

Applying Charles’ Law--Question 3e:

This question asked participants to graph the data that they would have collected from the previous question. Sam responds correctly regarding the shape of the graph, positive increasing linear line,

Then the graphs would be straight-line graphs with changes in temperature. [Plot] temperature [on y-axis] and volume [on x-axis] and so if you increase the temperature, the volume is going to go up.
However, Sam places the volume on the x-axis and temperature on the y-axis when the ideal response places temperature on the x-axis and volume on the y-axis.

*Figure 4.18: Sam’s Drawing for Question 3e of the Written Assessment*

![Diagram](image)

**Pedagogical Content Knowledge**

Pedagogical Content Knowledge (PCK) was assessed in two avenues in this study. The first avenue was to ask the participants if they would use in their own classrooms the apparatus presented in the first interview. Follow up questions asked how and why the apparatus would be used or not used. This line of questioning gave participants the opportunity to talk about their PCK in relation to the novel apparatus, thus demonstrating their understanding of the subject matter knowledge for teaching underlying the concepts for which the apparatus can be used, their pedagogical knowledge regarding the use of the apparatus, and their knowledge about learners in how the participants would present the apparatus and what their students would be asked to do with the apparatus. Here, the dynamic nature of PCK can be seen and, perhaps, documented.

The second avenue of assessing PCK was to ask the participants how they actually teach their unit on the Gas Laws. This information was obtained in the second interview. Participants were asked to provide lecture notes, worksheets, experiments and assessments in
addition to describing in detail how they teach their Gas Law unit. By discussing their practice and displaying artifacts, participants were able to talk through their thinking and decision making process that forms the foundation of lesson planning and execution.

These two methods of assessing PCK, discussion about the possible use of new apparatus and descriptions of actual classroom practice, illuminate the participants’ use of representations and their understanding of student conceptions. 

*Use of Apparatus Presented in Scenarios*

Regarding the first apparatus, the oil reservoir and glass tube where air is added to the reservoir (See Appendix B), Sam states that he would use the apparatus in class as an experiment if he had enough apparatus. He says that,

This would be better because we would get better pressure readings and pressure units. We currently do something simple—books and syringe. Plot the data and make a curve.

As an experiment, students would work in pairs; they would increase the pressure in the apparatus and record the volume decrease. He would ask the class to collect different data points. Sam would then set an equation so a constant results for the data and then come up with the relationship between pressure and volume.

Sam extends the experiment to include other variables. Sam goes on to say,

Of course, you could do this where you change temperature. And if you could ice bath the thing and have different temperatures, that might be another way to show the relationship with temperature with the pressure involved. So you could go through it first at room temperature and then ice bath it and then see that they’re going to get different volumes because of the influence of temperature on it.
When describing the objective(s) for the lesson, Sam states this his primary objective would be to show the relationship between volume and pressure as a constant. In addition, Sam continues with his idea of using the apparatus to include the variable temperature. Sam’s secondary objective would be to show the relationship with temperature, pressure and volume.

The second apparatus, the Erlenmeyer flask and tubing with the oil plug where the apparatus is moved from different temperature environments, was also proposed for possible classroom use. Sam did say he would use this apparatus over the capillary tube and hot oil experiment he uses now. He sees the capillary tube experiment as troublesome because the distance in millimeters on the capillary tube is very small. Students make frequent errors, such that when the distance is graphed as a proxy for volume, those small errors grow into large errors. The errors come into play when the graphs the students draw of their data are extrapolated to find absolute zero. Students’ extrapolated graphs result in an absolute zero being well beyond the negative 271 degrees Kelvin that absolute zero actually is. Sam states, Yeah, but one of the problems you have with using that capillary tube is that the distances are so short that just one small mistake can make a big mark if there’s a big margin error. Than with this the way we do it. Because most of the time, we end up—if we get within 20 degrees, we were considered pretty good. (laughs). Minus 291. That’s good.

When talking about his objectives for a lesson using the Erlenmeyer flask apparatus in his classroom, Sam states he would have three objectives,

Well, the objective is first of all just to see the relationship of Charles’ Law actually working before your very eyes. And then the other one is being able to use graphs to
predict—make predictions and come up with this nebulous number - the absolute zero. So you know, how you could possibly come up with it and if you had more accurate data collecting that you know you could maybe your pretty close to the value that this is theoretically predicted. So I think those two things that brings in graphing which I use a lot, with data collecting and labs –And to show them how you can use plotted data to come up with some conclusions.

Representations in Teaching Practice

In order to understand the representations used by Sam in his teaching practice, it is necessary to understand how he teaches his unit on Gas Laws. The following table outlines Sam’s curriculum in brief along with the representations focused on during each activity.

Table 4.8: Sam’s Curriculum of Gas Laws Unit

<table>
<thead>
<tr>
<th>Day</th>
<th>Curriculum</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>KMT (PowerPoint and simulation)</td>
<td>Particulate</td>
</tr>
<tr>
<td></td>
<td>1. Gases are made up of tine particles with no attractive or repulsive forces.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Particles move rapidly in constant random motion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Particle collisions are perfectly elastic with no loss of energy.</td>
<td></td>
</tr>
<tr>
<td>Day 2</td>
<td>Gas Pressure: Atmospheric pressure</td>
<td>Macroscopic</td>
</tr>
<tr>
<td></td>
<td>1. Crushing can demo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Upside-down cup of water demo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Ruler/Newspaper demo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Sipping on a straw demo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Other demos in video by Lee Merrick</td>
<td></td>
</tr>
<tr>
<td>Day 3</td>
<td>Gas Pressure: Barometers &amp; Units</td>
<td>Macroscopic</td>
</tr>
<tr>
<td></td>
<td>1. Shows various types of barometers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Lectures about different units of pressure and how to convert between the different units. (kPa, atm, mmHg, psi).</td>
<td>Symbolic</td>
</tr>
<tr>
<td>Day 4</td>
<td>Gas Pressure: STP and factors affecting gas pressure</td>
<td>Symbolic</td>
</tr>
<tr>
<td></td>
<td>1. Lectures about STP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Lectures about how amount of molecules, volume and temp. can effect gas pressure</td>
<td>Macroscopic and perhaps other</td>
</tr>
</tbody>
</table>
Day 5  
**Boyle's Law**  
1. Volume inversely related to Pressure based on prior demos  
2. PV=C and PV=P'V'  
3. 1957 Science film  
4. Vacuum pump demos with balloons, shaving cream and Peeps  
5. Vacuum pump demo to boil water  

Day 6  
**Boyle's Law**  
1. Lab-Syringe and textbook  
2. Problem sheet  

Day 7  
**Charles' Law**  
1. Volume directly related to Temp.  
2. V/T = C  
3. 1957 science film  
4. Balloon demo using inflated balloon and calculate volume at room temp and in dry ice.  

Day 8  
**Charles' Law**  
1. Lab-oil plugged capillary tube with graphing to extrapolate absolute zero  
2. Problem sheet  

Day 9  
**Gay-Lussac's Law**  
1. Done because in chapter  
2. Lecture for pressure directly related to temperature  
3. P/T=C  
4. Lecture on pressure cookers and altitude cooking  

Day 10  
**Combination Gas Law**  
1. Lecture on PV/T=C  
2. Problem sheet--math oriented mostly  

Day 11  
**Ideal Gas Law**  
1. PV/nT=R or PV=nRT  
2. Sing song  
3. The many possible combinations of P, V, T units to calculate R  
4. Problem sheet
Day 12  Avogadro's Hypothesis
1. Equal volumes at same temperature and pressure contain same number of particles and same volume.
2. STP will occupy 22.4L of volume
3. Lab—Equal volumes of O₂, N₂, CO₂

Day 13  Graham's Law of diffusion and effusion
1. Lecture of diffusion is inversely proportional to square roots of molecular weights.
2. For effusion lecture, Uses flat basketballs and pressurized cans of tennis balls as examples
3. Math relationship

Day 14  Graham's Law of diffusion
Lab—NH₃/HCl diffusion

Day 15  Review for test
Symbolic

Day 16  Test
Vocabulary—text
Multiple Choice—
Macroscopic and Symbolic
Problems—Symbolic

The four representations, that is, Macroscopic, Particulate, Symbolic, and Graphic, were used to examine Matthews’s teaching of the kinetic molecular theory, Boyle’s Law and Charles’ Law. Classroom instruction techniques such as experiments, demonstrations, activities, assignments and summative assessments were examined to identify the types of representations used for the specific student action.

Macroscopic Representation.

Sam uses the Macroscopic representation to illustrate Boyle’s and Charles’ Law. For Boyle’s Law, Sam uses the classic experiment of the syringe filled with air, a plunger placed into the syringe and textbooks added as pressure to the top of the plunger. Students are able to see directly that as more books are added (a proxy for pressure) the volume of air inside the syringe decreases.
Sam also conducts a number of demonstrations using a vacuum pump. In each demonstration, a substance, shaving cream, marshmallow candies or a partially inflated balloon, is placed into the vacuum pump and the pump is evacuated. Thus, as pressure is decreasing, the students can view the increase in the volume of the gas trapped in each of the substances.

The experiment Sam conducts using the macroscopic representation to show students Charles’ Law employs a capillary tube. A small capillary tube is plugged with hot oil trapping a volume of air in the tube. A ruler is attached to the capillary tube and the entire apparatus is submerged into a hot water bath. As the temperature rises, the volume of air trapped in the tube increases. Students record the distance measurement from the end of the capillary tube to the oil plug as temperature changes.

*Particulate Representation.*

Sam uses only one activity in his classroom that incorporates the particulate representation. The activity is a simulation of particles moving during the instruction of the kinetic molecular theory. Sam likes to use this simulation, obtained from a college or university website, to show that particles are in motion and that pressure, temperature and volume can effect the motion of the particles. Sam does not return to this site during the rest of his instruction of the Gas Laws.

*Symbolic Representation.*

Sam emphasized the symbolic representation while discussing his unit on gases. When conducting the syringe experiment, Sam has students collect different data points of pressure and volume. In a whole group class discussion, Sam selects a set of data points and mathematically shows that \( PV = \text{constant} \). He then selects another set of data points. Sam
then sets the two sets of data points equal to each other, since each set of data individually equals \( C \), and works through the mathematical transformations to come up with \( PV = P'V' \).

A number of problems are assigned to students to work through on the board, in their text and on worksheets. A considerable portion of the unit assessment is problems to be worked independent of context. Sam did not explicitly discuss the symbolic representation for Charles’ Law. However, throughout the interview he refers to problem sets for all of the gas laws that he teaches.

*Graphic Representation.*

The graphic representation is important to Sam. For the experiments to illustrate Boyle’s and Charles’ Law, graphing the data is emphasized. For Boyle’s Law, the syringe lab, the pressure data (books as a proxy) and the volume data of the air trapped in the syringe, are graphed. It is through the graph, as well as mathematically, that the relationship of volume and pressure are stressed in Sam’s class. His students come to understand Boyle’s Law chiefly through the use of graphic and symbolic representations.

For the experiment using the oil-plugged capillary tube submerged in a hot water bath to illustrate Charles’ Law, the data are graphed, not only to illustrate the relationship between temperature and volume but also to introduce and discuss the concept of an absolute temperature scale and absolute zero.

*Student Conceptions in Teaching Practice*

The first scenario (See Appendix B) is a sealed Erlenmeyer flask that is filled with air. An evacuation pump is connected to the flange in the flask and some of the air is pumped out. The pump is removed from the flange. Participants were asked to draw what
they thought their students would draw about the air particles in the flask after some of the air had been removed.

Sam predicted a number of student conceptions that he might see in the drawing. Sam initially reported that students might show molecules clustered around the hole that air was pumped out of (see Figure 4.19).

*Figure 4.19: Sam’s Drawing of Student Conceptions for the First Scenario of the Written Assessment*

He also mentions that students might think there are changes in pressure inside the flask depending on where inside the flask pressure is measured. For example, pressure near the hole where all of the molecules are clustered might have higher pressure than in the far corners of the flask where there are not any or only a few molecules. Sam also mentioned that the pressure would not increase because there are fewer particles so less interference for collisions and the particles are moving faster because of the “sucking out” and fewer particles in the flask.

When questioned about how he would address this alternate conception in his teaching, Sam suggested two possible ways to explain the “correct” answer to his students.
First, Sam would address these alternate conceptions by talking about the kinetic molecular theory. He would have students “look up the kinetic molecular theory”, “repeat and review their answers” in light of the kinetic molecular theory.

Sam also suggested that he could remind students about the elasticity of the molecules that we consider under the Ideal Gas Law. Sam would remind students that there is not an increase in speed of the particles and that there will still be perfectly elastic collisions. There will be no loss of energy. Thus, molecules clustering around the hole will not occur.

The second scenario (See Appendix B) showed a cross-section of a steel tank full of hydrogen gas. The hydrogen molecules are drawn as dots in the tank. Again, participants were asked to predict what they think their students will show of the cross-section when the tank is cooled.

This was a very complex problem for Sam. Initially, Sam was very concerned about how much gas is in the tank and how much the temperature is being lowered. While Sam eventually reconciled his concern about the amount of gas in the tank, the temperature of the tank continued to be an issue. Sam states,

Given the information about how much gas or how much the temperature is being lowered, I would think of the molecules were slowing down but then, as the temperature is lowered, they may form hydrogen liquid. And then could solidify. You know, depending upon the temperature change. If it was a small temperature change, then the gas molecules would still be evenly, you know, distributed but it won't be moving as fast as they were when the temperature was higher. As the temperature lowers, then they have lower kinetic energy, they would tend to lose their
kinetic energy that able to have the amount of translational energy that they would have at higher temperatures. And then change into a liquid as they just have the vibrational energy and rotational energy. So I—and I could foresee some of them showing the molecules—you know, showing it being there on the outside of the molecules concentrating to the center – But they still have the same kinetic energy, although depending upon how you're cooling it, you know. If you cool it—if you're just cooling the pipe – Then the molecules on the outside are going to have less kinetic energy than the ones on the inside. So that would cause uneven distribution of molecules but their speeds and then, of course, the liquification would be forming on the outside, I mean, closer to the steel pipe first—Than they would in the middle. I guess you know if we talked about liquid, solids and gases before this, that they would kind of put together the changes—just like we usually do it with water - You know, showing the phase changes that occur with the differences in temperatures and setting up with the hydrogen bonding in the water –But with all states of matter, temperature is the—and the amount of energy that molecules possess determines whether they're solid, liquid or gas.

Sam mentions that he thinks most of his students would draw the correct answer. After much prodding, Sam did suggest a couple of alternate conceptions.

Figure 4.20: Sam’s Drawing of Student Conceptions for the Second Scenario of the Written Assessment
First, Sam showed dots clustered in the center of the tank. However, this drawing might be valid based on how much the temperature is lowered. Sam goes on to explain that if the temperature is lowered too much, a liquid would result and then the drawing would be valid, showing a gas condensing into a liquid.

Assuming the steel tank is just being cooled, the molecules near the tank will have less kinetic energy than the molecules near the center of the tank. This would cause an uneven distribution of molecules and liquefication would be forming closer to the walls of the steel tank before it would occur in the middle. Sam also mentions translational energy at higher temperatures and then molecules only have vibrational and rotational energy as they change into a liquid. Sam’s concern for the unknown lowering of temperature resulted in the many possible “correct” answers to this scenario.

When asked about how he would address alternate conceptions in his teaching, Sam said he would refer back to the kinetic molecular theory. Molecules move in a straight line and keep moving until they collide with something—be it another molecule or the side of the container. Molecules are going to bounce back from the sides of the tank; they are not just going to stop moving. There will be molecular distribution even close to the edges of the cylinder.
CHAPTER FIVE
CROSS-CASE FINDINGS

This chapter will present cross-case analysis of the participants’ subject matter knowledge for teaching and curriculum as it relates to representations and student conceptions. Recall, PCK is that “special amalgam that is uniquely the province of teachers—separates the content specialist from that of the pedagogue” (Shulman, 1987, p.8). Information from the subject matter knowledge for teaching assessment, semi-structured interview and collected artifacts for each participant was presented in Chapter Four and are discussed at greater length there.

Background

Table 5.1 below shows demographic characteristics of the teachers and their schools. The participants shared many characteristics. All four participants held degrees in chemistry, a specification for the present study, but additionally all four held Master’s degrees, three in Education and one in Biochemistry. Three of the four participants received their licensure and Master’s degrees from the same institution. Three of the four participants taught at private schools. All four participants taught primarily 11th grade students; chemistry was an elective course for those students.

| Table 5.1: Participants’ Characteristics Related to Teaching |
|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Erik                          | Julien                        | Matthew                      | Sam                          |
| Degree(s)                     |                               |                               |                              |
| B.S. Chemistry                | B.S. Chemistry                | B.S. Chemistry                | B.S. Chemistry                |
| M.Ed.                         | M.Ed.                         | M.Ed.                         | M.S. Biochemistry             |
| Licensure                     | U of M                         | U of M                         | U of M                         | Unknown                      |
There are also some differences. Sam has been teaching for forty years while each of the remaining participants has less than ten years’ experience. Julien and Sam’s student populations are very diverse while Erik’s and Matthew’s student populations are relatively homogeneous. Julien teaches in an urban school while Erik and Matthew are located in the suburbs. Sam’s school might be considered rural since it is located 70 miles from a major
metropolitan area. Both Erik and Sam teach with a mix of block and regular scheduling during the week, whereas Julien and Matthew teach with a regular bell schedule with no blocks.

Subject Matter Knowledge for Teaching the Gas Laws

Subject matter knowledge for teaching influences the representations and alternate conceptions that make up PCK. Conversely, the representations and alternate conceptions of PCK influence subject matter knowledge for teaching. The subject matter knowledge for teaching assessment and the first interview were conducted simultaneously for each participant. Table 5.2 below shows the scores of the assessment for all participants.

Table 5.2: All Participants’ Subject Matter Knowledge for Teaching Assessment Scores

<table>
<thead>
<tr>
<th>Item</th>
<th>Erik</th>
<th>Julien</th>
<th>Matthew</th>
<th>Sam</th>
<th>Chemistry Concept</th>
<th>Targeted Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>1b</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2a</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>Identifying pressure and volume differences</td>
<td>Macroscopic</td>
</tr>
<tr>
<td>2b</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>Kinetic molecular theory</td>
<td>Particulate</td>
</tr>
<tr>
<td>2c &amp; 2d</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>Applying Boyle’s Law</td>
<td>Any representation was accepted</td>
</tr>
<tr>
<td>2e</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>Applying Boyle’s Law</td>
<td>Graphic</td>
</tr>
<tr>
<td>3a</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>Predicting gas volume changes</td>
<td>Macroscopic</td>
</tr>
<tr>
<td>3b</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>Applying Charles’</td>
<td>Any representation</td>
</tr>
</tbody>
</table>
Kinetic Molecular Theory--Question 1a & 1b:

Question 1a focused on the assumptions of the kinetic molecular theory and the appropriateness of representations of gas molecules drawn within the closed container shown in the test item. (See Appendix D for questions, ideal responses, chemistry concept addressed by the question, and the representation that was targeted by the question.)

Question 1b focused on the assumptions of the kinetic molecular theory and differences in the behavior of the gas molecules within a closed container when the variable of heat was added to the scenario.

What was understood about the kinetic molecular theory

The understanding of the kinetic molecular theory by the participants was limited at best. All participants stated that molecules are in constant random motion. Erik is the only participant who stated that collisions between molecules and sides of the container create pressure. Sam stated that when the heat is added to the scenario that the molecules would move faster and have more kinetic energy. Thus, there would be more pressure. Sam does not define pressure. The kinetic molecular theory is composed of four postulates (see Appendix D and E). The participants consistently mention only one postulate, namely that molecules are in constant random motion. Not mentioned by the participants are equal numbers of molecules or moles of oxygen and carbon dioxide. Molecules collide with one
another and sides of container to create pressure. Molecules would take up the entire space of the container, in the sense that there would be even distribution of O_2 and CO_2 in container.

*What was not understood about the kinetic molecular theory*

There were a number of alternate conceptions held by the participants. Both Julien and Sam said that gravity would impact the CO_2 molecules in the flask such that they would stay mostly towards the bottom of the flask. Sam did eventually say that through diffusion the CO_2 and O_2 would mix but he did not definitively state that both gases would be evenly distributed throughout the flask. Both Julien and Sam applied a macroscopic representation, gravity, to a particulate representation of gas molecules in a flask.

Another alternate conception appeared when both Erik and Matthew focused on the two gases having the same kinetic energy. Thus, since the oxygen molecule is lighter, it would be moving faster to have the same kinetic energy as the heavier carbon dioxide molecule. Erik stated that the molecules “are gaining kinetic energy from the heat and that is going to – I mean that [the molecules] are moving faster.” Julien also discusses kinetic energy of the molecules when heat is added to the scenario in question 1b. He states that the molecules would have a higher kinetic energy because there are more collisions between the now faster moving molecules. While both Erik and Matthew introduce Graham’s Law of diffusion to discuss the velocity of a gas molecule relative to its molar mass, it is not appropriate in this scenario for the questions asked during the subject matter knowledge for teaching assessment.

A third alternate conception of the molecules motion in the flask is Erik’s statement that the different shapes of the molecules would impact the rotation of the molecules. Erik
states that the carbon dioxide molecules are of a bent shape causing different rotations that would then impact the momentum of each molecule. Aside from the alternate conceptions regarding rotation and momentum, Erik’s statement of the shape of CO$_2$ is incorrect. Due to the double bonds between the oxygen and carbon atoms, the shape of CO$_2$ is linear.

These alternate conceptions are not mentioned in the literature of student alternate conceptions (Nussbaum, 1985; Robinson & Nurrenbern; Novich & Nussbaum, 1978, 1981; Lin, Cheng & Lawrenz, 2000) or teacher alternate conceptions (Lin, Cheng & Lawrenz, 2000; Kruse & Roehrig, 2005). It appears that the alternate conceptions the participants hold are new to the research base.

**Boyle’s Law**

This set of five related questions focused on the ability of the participants to identify pressure and volume differences, explain their response for a novel situation, and apply Boyle’s Law to a novel situation. (See Appendix D, for questions and ideal responses. See Appendix B for scenario.)

*What was understood about Boyle’s Law*

Each participant could correctly predict what would happen to the level of oil in the glass tube. Everyone said that the level of the oil in the glass tube would rise. In explaining why the level of the oil in the glass tube would rise, a variety of responses was obtained. The most thorough response was Matthew’s. He stated that eventually the pressure from the added molecules in the reservoir will equalize with the pressure from the collisions of the air molecules trapped in the glass tube. He also stated that an increase of pressure on the oil in the reservoir will cause the level of the oil in the reservoir to drop, thus forcing the oil in the glass tube to rise and thereby put more pressure on the air trapped in the glass tube and thus
decrease the air’s volume. This is the key to understanding at a deep level the chemistry concepts at work here.

*What was not understood about Boyle’s Law*

The scenario presented for Boyle’s Law was a two-system problem. The first system is that of the air trapped in the reservoir. The second system is that of the air trapped in the glass tube. They are connected through the oil in the apparatus. The key to understanding this two-system problem at a conceptual level is to realize that eventually the pressure from the added air molecules in reservoir will equalize with the pressure from the collisions of the air molecules trapped in the glass tube. Participants’ responses to this two-system problem evidenced their superficial understanding of Boyle’s Law.

Erik and Julien’s responses were very limited. Both of them focused on the reservoir. The discussed how the added air molecules in the reservoir would cause more collisions and thus more pressure, but in the reservoir only. A connection was not made between the pressure in the reservoir and that in the glass tube. Erik and Julien may not have seen this scenario as a two-system problem since they only focused on only one of the systems.

Another example of not linking the two systems together for this scenario was Sam’s. Sam does not talk about increased frequency of collisions of the molecules because the added air exerts more pressure on the oil in the reservoir. Sam talks about the surface area of the oil in the reservoir being large so the force acting on such a large surface area will increase pressure. Sam is clearly describing pressure from a physics perspective instead of a chemistry perspective. In focusing on pressure as force exerted over surface area, Sam is also missing the connection between the two systems. He is focusing only on the surface
area of the oil in the reservoir. Lin, Cheng, & Lawrenz (2000) saw similar results in their study regarding a different scenario; however, that scenario was a two-system problem.

A second component of Boyle’s Law is that the equation, $P_1V_1 = P_2V_2$, itself describes an end state of pressure and volume after change has occurred. The equation has its power in being able to predict a final result of change. For example, what is the pressure that a gas exerts on its new container if it is transferred from a 200 liter tank with a pressure of 1/24 atm to a 5 liter container with no change in temperature? Boyle’s Law cannot be used to explain why the change occurs or what is happening to individual molecules or atoms of gas in the container – it simply allows for macroscopic predictions of behavior. However, that was not the case with the participants in this study. Both Erik and Julien attempted to apply the Boyle’s Law equation to explain why a change in volume of the gas trapped in the glass tube was occurring. The nature of Boyle’s Law describing an end-state is not discussed in the literature (de Berg, 1985).

Another alternate conception was the random application of gas law equations to a novel situation (Lin, Cheng, & Lawrenz, 2000). Matthew used the Ideal Gas Law equation, $PV = nRT$, to answer the question. The Ideal Gas Law equation appeared to be selected almost randomly as Matthew was crossing off the variables that needed to be eliminated to match his conception of the scenario. This resulted in Matthew’s selection of incorrect variables, volume and temperature, to apply Boyle’s Law.

Charles’ Law

A new apparatus and scenario were presented to the participants for this series of five questions. (See Appendix D for questions and ideal responses. See Appendix B for scenario.) These questions asked participants to predict the direction the oil plug would
move in the apparatus if the apparatus were to be moved to a colder environment, provide an explanation for their reasoning, and apply Charles’ Law to the novel scenario.

*What was understood about Charles’ Law*

Similarly to question 2a, each participant was able to correctly predict which way the oil plug would move when the apparatus was moved to a colder environment, unlike the participants in the study conducted by Lin et al (2000), were almost 50% of the students and teachers gave the incorrect prediction.

*What was not understood about Charles’ Law*

Similar to the scenario assessing Boyle’s Law, the key to this scenario is to understand that at some point pressure will equalize between the outside of the oil plug and the pressure inside the flask apparatus. If pressure is not understood to be equal inside the apparatus and outside the apparatus, participants will not explain this scenario correctly. Of the four participants, only Matthew mentioned that pressure will equalize. However, as he continued to answer the question, he began to talk about pressure and temperature as the changing variables with volume remaining constant. This is similar to Lin et al (2000) findings where only 20% of students and teachers could provide a correct explanation.

Because they failed to grasp the concept of equalization of pressure, each of these participants incorrectly identified the changing variables as temperature and pressure. Once pressure and temperature were “identified” as the changing variable, participants held on to that alternate conception throughout the rest of the interview including graphing the incorrect variables. By holding on to alternate conceptions throughout the scenario, participants illustrate a superficial understanding of Charles’ Law.
Similarly to Boyle’s Law, the Charles’ Law equation, \( \frac{V_1}{V_2} = \frac{T_1}{T_2} \), itself describes an end state of temperature and volume after change has occurred. The equation has its power in being able to predict a final result of change. Charles’ Law cannot be used to explain why the change occurs or what is happening to individual molecules or atoms of gas in the container – it simply allows for macroscopic predictions of behavior. However, that was not the case with the participants in this study. All of the participants attempted to use the Charles’ Law equation to explain why a change in volume of the gas trapped in the flask and tubing was occurring. The nature of Charles’ Law describing an end-state is not discussed in the literature (de Berg, 1985). Perhaps a conceptual understanding of Charles’ Law would have yielded more correct responses throughout the interview.

**Implications**

The subject matter knowledge for teaching assessment shows a superficial understanding of the targeted chemistry concepts. Since the participants appear to have only a superficial understanding of the kinetic molecular theory, Boyle’s Law, and Charles’ Law, it is highly improbable that they are teaching toward deep, conceptual understanding for their students. In addition, each of the participants holds similar alternate conceptions as the literature documents in students (Kruse & Roehrig, 2005; Lin, Cheng & Lawrenz, 2000). Those alternate conceptions may in fact be directly taught to the participants’ students (Kruse & Roehrig, 2005).

**Pedagogical Content Knowledge**

Pedagogical Content Knowledge (PCK) was assessed in two ways. The first method was to analyze the subject matter knowledge for teaching with respect to the targeted representations that corresponded to each question. Through scoring of the participants
responses using the rubric developed for this study, the participants understanding of each representation as well as their ability to transfer between the representations can be determined.

The second way of assessing PCK was to ask the participants how they actually teach their unit on the Gas Laws. This information was obtained in the second interview. Participants were asked to provide lecture notes, worksheets, experiments and assessments in addition to describing in detail how they teach their Gas Law unit. By discussing their practice and teaching artifacts, participants were able to display the thinking and decision making processes that form the foundation of their lesson planning and execution. Here, the dynamic nature of PCK can be seen and perhaps, documented. In using these two methods of assessing PCK, the representations that the participants use and their understandings of student conceptions was illuminated.

*Representations Used by Participants on Subject Matter Knowledge for Teaching Assessment*

From the low scores on the subject matter knowledge for teaching assessment, the participants demonstrated a superficial understanding of the kinetic molecular theory, Boyle’s Law, and Charles’ Law. Further analysis of the assessment focusing on the targeted representations that corresponded to each question revealed a superficial understanding of representations.

Of the four representations, macroscopic, particulate, symbolic, and graphic, all four participants in the two instances used the macroscopic representation correctly where the macroscopic representation was the targeted representation. The participants used the other representations, particulate, symbolic, and graphic, inconsistently and incorrectly. These
data support the claim that the participants did not demonstrate a transfer between representations. Julien and Matthew’s responses to the graphic representation in the Charles’ Law scenario will serve as an example.

Julien and Matthew were very confused when asked to graph the data that was collected in question 3c and 3d. Both participants chose the incorrect variables to graph. Julien, having mentioned using the distance the oil plug moves as temperature changes, chose to graph temperature on the x-axis and centimeters/question mark on the y-axis. For Julien, the change in distance the oil plug moves became the variable instead of being recognized as a proxy for volume. Julien did not draw anything on his graph once he selected the variables for the axes. Matthew, still thinking that pressure and temperature are the variables changing, graphed temperature on the x-axis and pressure on the y-axis. Matthew did draw a positive linear line; however, his variables were incorrect. Both Julien and Matthew are unable to transfer between the representations to form a conceptual understanding of Charles’ Law.

Only Sam showed some flexibility in transferring between representations. Sam uses the particulate, symbolic and graphic representations to answer questions 3b & 3c targeting the application of Charles’ Law to a novel scenario (see Appendix D for ideal responses and Appendix B for the scenario). Sam begins his response with the particulate representation of molecules moving faster, creating more pressure and increasing the volume of the gas trapped in the apparatus. Sam then moves to the symbolic representation when talking about the data he would collect; the flask and tubing can be measured as a proxy for volume of the gas trapped in the apparatus. Sam then extends his response to include the graphic representation by stating that once volume data has been collected for various temperatures, a
graph can be produced. However, Sam does not state what purpose the graph would serve and does not state that the temperature scale on this graph must be Kelvin.

**Implications**

From the subject matter knowledge for teaching assessment focusing on the targeted representations assigned to each question, it seems clear that the participants are not able to transfer from one representation to another. Most chemistry courses are taught in the symbolic representation; i.e. electron configuration, chemical formula, chemical reactions, equations and graphs. A majority of teachers do use the symbolic representation in their classrooms and assume that the underlying concepts are understood (Niaz & Robinson, 1992). The literature does not support the idea that symbolic representation competence will lead to a conceptual understanding of molecular concepts (Nakhleh 1993; Nurrenburn and Pickering 1987; Pickering 1990; Sawrey 1990). The participants in the present study do not show an ability to transfer between representations, which indicate a superficial understanding of the chemistry concepts targeted in this study and leads one to the question the impact that such a superficial conceptualization has upon their students?

**Representations in Teaching Practice**

In order to understand the representations used by each participant in his teaching practice, it is necessary to understand how he teaches his unit on Gas Laws. Analysis of all participants’ curricula revealed a wide variety of topics, experiments, demonstrations, and representations taught in each unit. Since the subject matter knowledge for teaching assessment focused on the kinetic molecular theory, Boyle’s Law, and Charles’ Law, each participant’s curriculum was examined for those three topics (see Table 5.3), though it should be noted that one of the participants did not teach the kinetic molecular theory. At the end of
the unit, all participants provided students with a unit review assignment and a summative assessment. The review assignments and summative assessments are analyzed here as well.

*Kinetic Molecular Theory*

Erik was the only participant who did not teach the kinetic molecular theory in his unit on the Gas Laws. Recall that Erik chose to use the curriculum provided for him by the science department at his school. In the department curriculum materials, the kinetic molecular theory is not taught as part of the Gas Laws. It is possible the kinetic molecular theory is taught in another unit during the course but it is not referenced here. This may also be due to the fact that the textbook used for this course does not include the kinetic molecular theory in the chapter on the Gas Laws.

Julien, Matthew and Sam all teach the kinetic molecular theory using the particulate representation. Both Julien and Matthew use the textbook’s treatment of the kinetic molecular theory. Julien’s text places the kinetic molecular theory in the middle of the unit after instruction on the properties of gases, particularly pressure, atmospheric pressure and measuring pressure. Julien’s text also uses a particulate analogy of dancers on a dance floor to help illustrate the particulate representation of atoms or molecules of gas in a container. Matthew’s text opens the unit on Gas Laws with the kinetic molecular theory, although the textbook also presents the kinetic molecular theory in the previous chapter on states of matter. Sam is similar to Matthew in that Sam begins his unit on the Gas Laws with instruction on the kinetic molecular theory. Sam uses two online sources for his instruction of the kinetic molecular theory.

*Boyle’s Law*
In teaching Boyle’s Law, Erik and Sam seemed to approach instruction similarly. Both lectured and gave notes about Boyle’s Law to start their lessons. Erik used a demonstration with a syringe to increase pressure and reduce the volume of a gas. Sam did something similar except that he chose to use a vacuum pump to reduce pressure to show an increase in volume of a gas. However, Sam does not take into account that he is also changing the number of molecules in the system as well. Sam does not realize that by attempting to simplify the phenomena for his inexperienced learners, he is in fact distorting the phenomena he is trying to illustrate (Geddis, 1993). For an experiment for Boyle’s Law, Erik, Julien and Sam chose the same experiment using the macroscopic representation. The experiment (see Figure 5.1) is a syringe in a vertical position clamped to a ring stand.
Table 5.3: All Participants’ Curriculum and Representations

<table>
<thead>
<tr>
<th></th>
<th>Erik</th>
<th>Julien</th>
<th>Matthew</th>
<th>Sam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Curriculum</strong></td>
<td><strong>Representation</strong></td>
<td><strong>Curriculum</strong></td>
<td><strong>Representation</strong></td>
<td><strong>Curriculum</strong></td>
</tr>
<tr>
<td>Kinetic</td>
<td></td>
<td>1. Discussion about balloon inflation due to</td>
<td>1. Prior Knowledge-what do kids know about gases</td>
<td>1-5: Particulate</td>
</tr>
<tr>
<td>Molecular</td>
<td>Not taught</td>
<td>air particles.</td>
<td>2. 5 statements in text and discuss differences</td>
<td></td>
</tr>
<tr>
<td>Theory</td>
<td>2. Hand motions for each part of KMT (4 bullets) in text.</td>
<td>3. Ideal vs. Real discussed as part of 5 statements</td>
<td>3. Ideal vs. Real discussed as part of 5 statements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. KMT model problem in text where atoms are “dancers”.</td>
<td>4. Expansion of gases based on 5 statements.</td>
<td>4. Expansion of gases based on 5 statements.</td>
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<tr>
<td></td>
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<td>5. Homework from text</td>
<td></td>
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<tr>
<td><strong>Boyle’s Law</strong></td>
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<tr>
<td></td>
<td>1. Packet for entire unit given out with a place for notes and problems for each law.</td>
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<td></td>
<td>2. Demo--Syringe</td>
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<td></td>
<td>Show syringe and as the plunger is pushed the volume of air in syringe gets smaller.</td>
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<tr>
<td></td>
<td>3. Lab--Syringe and 2L pop bottle full of water as a proxy for pressure.</td>
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<tr>
<td></td>
<td>4. Graph data</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1. Symbolal</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>2. Macro</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>1. Lab-- Syringe and books as a proxy for pressure.</td>
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<tr>
<td></td>
<td>1. Macro</td>
<td></td>
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<tr>
<td></td>
<td>2. Graph data</td>
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<tr>
<td></td>
<td>3. Problems on back of lab</td>
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<td></td>
<td>4. Graphic</td>
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<tr>
<td><strong>Charles’ Law</strong></td>
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<td></td>
<td>1. Packet for notes and problems</td>
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<td></td>
<td>2. Demo-- Balloon/flask Flask with a little water in bottom is sealed with a balloon. Apparatus is placed on burner and the balloon inflates. Apparatus is then placed in an ice water bath and the balloon is “sucked” into the flask.</td>
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<tr>
<td></td>
<td>1. Symbolal</td>
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<tr>
<td></td>
<td>2. Macro</td>
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<td></td>
<td></td>
<td>1. Macroscopic</td>
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<td></td>
<td></td>
<td>2. Graphic</td>
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<td>3. Graphic</td>
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<td>4. Graphic</td>
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<td>5. Mostly symbolic with 3 particulate</td>
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<td><strong>Combined Gas Law</strong></td>
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<tr>
<td><strong>Boyle’s Law</strong></td>
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<tr>
<td></td>
<td>1. Volume inversely related to Pressure based on prior demos. PV=C and PV=PV’</td>
<td>1. Macroscopic</td>
<td>4.  Practice Problems (3 days of problems)</td>
<td></td>
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<tr>
<td></td>
<td>2. 1957 Science film</td>
<td>2. Class discussion</td>
<td>5. Demo-marshmallow in syringe</td>
<td></td>
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<tr>
<td></td>
<td>3. Vacuum pump demos with balloons, shaving cream and Peeps, and to boil water</td>
<td>3. Lecture showing Boyle and Charles Law</td>
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<tr>
<td></td>
<td>4. Lab-Syringe and books as a proxy for pressure.</td>
<td>4. Symbolic</td>
<td>5. Macroscopic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Problem sheet</td>
<td>5. Symbolic</td>
<td></td>
<td></td>
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<tr>
<td><strong>Charles’ Law</strong></td>
<td></td>
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<tr>
<td></td>
<td>3. Balloon demo using inflated balloon and calculate volume at room temp and in dry ice.</td>
<td>3. Macroscopic</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>4. Lab-oil plugged capillary tube that is cooled. Distance of oil plug is proxy for volume.</td>
<td>4. Macroscopic</td>
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<tr>
<td></td>
<td>5. Graph data to extrapolate absolute zero</td>
<td>5. Graphic</td>
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<td></td>
</tr>
</tbody>
</table>

147
| Assessment | Review Test | Symbolic Symbolic | Section Summary questions Quiz | Macroscopic, Symbolic and Particulate Symbolic | Review with Review Packet Test | Symbolic Primarily symbolic but one particulate and a few macroscopic | Review for test Test | Symbolic Symbolic |

The air trapped in the syringe is the gas being measured. Both Julien and Sam use books placed on top of the plunger as a proxy for pressure. Erik uses a two-liter soft drink bottle to which water is added at the rate of 100 mL at a time as a proxy for pressure. Erik, Julien, and Sam have students collect the volume of gas in the syringe by reading the scale on the syringe as well as the pressure being applied in number of books or milliliters of water. These data are then graphed—the graphic representation. Julien and Sam follow this experiment with a worksheet of symbolic representation problems (see Figure 5.2).
Matthew is unique in his instruction of Boyle’s and Charles’ Law. Matthew teaches Boyle’s Law and Charles’ Law as special cases of the Combined Gas Law. Thus, Matthew focuses on how the variables of pressure, temperature, and volume are interacting with one another in any given gas law scenario. Matthew conducts demonstrations with a large syringe to show how a change in pressure impacts volume and temperature; he places a large marshmallow in a large syringe to illustrate how changes in pressure, due to the pushing or pulling of the syringe, change the volume of gas trapped in the marshmallow. A second demonstration is to place some warm water in the large syringe and change the pressure so that the water “boils”. Both of these demonstrations use the macroscopic representation. However, the water “boiling” is more complex than the macroscopic representation implies. Matthew does not seem to recognize the complexity of that demonstration. Matthew also has students do practice problems using the variables of pressure, temperature, and volume (see Figure 5.3).
Figure 5.3: Example of a Practice Problem Used by Matthew

1. The highest recorded atmospheric pressure was 1.072 atm. If we place a 3.00 L balloon in a chamber with this pressure and lower it to 0.871 atm (the record low), and keep the temperature constant, what is the new volume of the balloon?

Charles’ Law

Erik uses lecture, a demonstration, and practice problems for his instruction of Charles’ Law. The demonstration is of an Erlenmeyer flask containing a small amount of water capped by a latex balloon (see Figure 5.4).

Figure 5.4: Erik’s Demonstration of Charles’ Law

The entire apparatus is placed on a burner and the balloon eventually inflates. The apparatus is then placed in an ice water bath and the balloon is “sucked” into the flask (see Figure 5.4). This demonstration is of the macroscopic representation and is used as an example of Charles’ Law. Erik did state that he does try to ask students to make predictions before his demonstrations; however, he does not always remember to do so. Nor does he always follow up the demonstration with a class discussion. Students are not confronted with their alternate conceptions during these demonstrations in Erik’s classroom. Erik tells the students the “correct answer” for how the specific law they are
studying applies to the demonstration. Students are then asked to do practice problems using the symbolic representation (see Figure 5.5).

*Figure 5.5: Erik’s Example of Student Practice Problem for Charles’ Law*

Both Julien and Sam use demonstrations with balloons and dry ice to illustrate Charles’ Law. While Sam fills the balloon with air and then places the balloon in dry ice, illustrating a change in volume of the balloon with a change in temperature, Charles’ Law; Julien fills the balloon with dry ice. It is unclear how Julien sees the filling of the balloon with dry ice to be a macroscopic representation of Charles’ Law. Both Julien and Sam have students conduct an experiment to demonstrate Charles’ Law. Sam uses an oil-plugged capillary tube that is cooled (see Figure 5.6) to collect data of different temperatures and volume of gas trapped in the capillary tube. Students then graph the data to see the relationship between temperature and volume as well as to introduce the concept of absolute zero. Julien’s textbook uses the same oil-plugged capillary tube that Sam uses. However, Julien chose to deviate from his text and use a different experiment. Julien uses copper balls affixed with pressure gauges, which he places into different temperature water baths. However, Julien is actually demonstrating, not Charles’ Law, but rather Gay-Lussac’s Law where a change in temperature is related to a change in pressure.
Students mark on the capillary tube the location of the oil plug is at specific temperatures. Those data are then graphed and extrapolated for absolute zero. The graphic representation assignment is then followed by practice problems using the symbolic representation (see Figure 5.7).

**Figure 5.7: Sam’s Example of Practice Problems Using Symbolic Representation**

9. What temperature (in °C) is needed to change 8.31 liters of a gas at 27.1 °C to a volume of 10.6 liters?

Only Julien’s textbook includes questions that use the particulate representation on the assignment following the experiment (see Figure 5.8).
As stated earlier, Matthew teaches Charles’ Law as a special case of the Combined Gas Law. Matthew also focuses on the macroscopic and symbolic representations during his instruction.

Unit Review Assignment and Summative Assessment

All participants gave students a unit review assignment toward the end of the unit in preparation for the unit summative assessment. Erik uses the review assignment provided to him by his department. Matthew uses the review assignment from his textbook. Sam writes his own review assignment. Erik, Matthew and Sam’s unit review assignments used only the symbolic representation (see Figure 5.5). Julien’s unit review assignment is the section summary questions from his text. These questions use the macroscopic, particulate and symbolic representations (see Figure 5.8).

All participants give students a summative assessment. The assessments vary in length and weight for grading purposes. Erik, Julien and Sam’s summative assessments use only the symbolic representation (see Figure 5.9).
Figure 5.9: Julien’s Example of Symbolic Representation Summative Assessment

Question

6. A hot air balloon at 0.9 atm pressure in Minneapolis has a volume of 1200 liters. As the balloon rises to an altitude of 800 meters the pressure on the balloon is 0.7 atm. What is the volume of the balloon now?

Matthew is the only participant who uses multiple representations. Matthew’s summative assessment includes multiple choice questions that use the symbolic, particulate and macroscopic representations, one essay question about the kinetic molecular theory that uses the particulate representation, and four problems that student must work out that using the symbolic representation (see Figure 5.10).

Figure 5.10: Matthew’s Example of Macroscopic and Particulate Representation

Summative Assessment Question

9. Suppose that two gases with unequal molar masses were injected into opposite ends of a long tube at the same time and allowed to diffuse toward the center. They should begin to mix
   a. closer to the end that held the lighter gas.
   b. in approximately five minutes.
   c. exactly in the middle.
   d. closer to the end that held the heavier gas.

Essay

Given the 5 assumptions of the kinetic molecular theory
a) Gases consist of large numbers of tiny particles that are far apart relative to their size.

b) Collisions between gas particles and between particles and container walls are elastic collisions.

c) Gas particles are in continuous, rapid, random motion. They therefore possess kinetic energy, which is energy of motion.

d) There are not forces of attraction or repulsion between gas particles.

e) The average kinetic energy of gas particles depends on the temperature of the gas.

1. Use the kinetic-molecular theory of gases to explain Compressibility
   (Hint – define the term and relate it to the correct assumption).
Summary

The four representations, macroscopic, particulate, symbolic, and graphic, were used to examine the participants’ teaching of the kinetic molecular theory, Boyle’s Law and Charles’ Law. Classroom instruction such as experiments, demonstrations, activities, assignments, and summative assessments were examined for the types of representations used for the specific student action. In addition to frequency of the representation used, it is also important to note when the representation was used. That discussion will follow.

MacROscOPIC Representation

The macroscopic representation was used heavily, primarily in demonstrations and experiments for all of the participants. Julien and Sam used the macroscopic representation more than their fellow participants, each conducting more demonstrations in their classrooms for Boyle’s and Charles’ Laws. Julien was unique in that he used the macroscopic representation for the unit review assignment.

Particulate Representation

Erik never used the particulate representation in his instruction. Erik also did not teach the kinetic molecular theory where the data show the particulate representation used most often. Matthew and Sam used the particulate representation primarily for instruction of the kinetic molecular theory. Sam never used the particulate representation after his instruction of the kinetic molecular theory. Matthew used the particulate representation again only for his essay question on the kinetic molecular theory on the unit summative assessment.

Julien was unique in his use of the particulate representation. The particulate representation was used at least once during instruction for the kinetic molecular theory,
Charles’ Law and the unit review assignment. However, this may be due to Julien’s textbook, Chemistry in the Community, which he rigorously follows. Julien did not use the particulate representation for Boyle’s Law or on the unit summative assessment.

Symbolic Representation

While all participants utilized the symbolic representation, Erik and Sam seemed to use it the most (see Table 5.3). Both Erik and Sam used practice problem worksheets in their curricula frequently. Matthew used practice problem worksheets or problem assignments from the textbook as well in his curriculum. However, Matthew’s use does not seem as heavy as Erik and Sam’s. Julien used the symbolic representation only twice during his instruction of Boyle’s and Charles’ Law. However, all participants used the symbolic representation for the unit review assignment and three of the four used only the symbolic representation for the unit summative assessment.

Graphic Representation

Matthew never used the graphic representation in his instruction on the kinetic molecular theory, Boyle’s Law, and Charles’ Law. Erik, Julien and Sam used the graphic representation when they had students graph their data collected from the same experiment they all conducted for Boyle’s Law. This was the only time Erik used the graphic representation. Julien and Sam used the graphic representation during instruction on Charles’ Law when they both had students graph experimental data and extrapolate for absolute zero. None of the participants used the graphic representation as part of the unit review assignment or the unit summative assessment.
Student Conceptions in Teaching Practice

As part of the first interview, participants were asked to predict student conceptions of two scenarios involving the behavior of gases, primarily focusing on alternate conceptions of the kinetic molecular theory.

The first scenario (see Appendix B) is a sealed Erlenmeyer flask that is filled with air. An evacuation pump is connected to the flange in the flask and some of the air is pumped out. The pump is removed from the flange. Participants were asked to draw a diagram showing how they thought their students would illustrate the air particles remaining in the flask after some of the air had been removed.

Each of the four participants provided a different response to this question. Erik thought his students might draw the molecules of air “really big with not much space, if any, between the molecules”, as seen in the literature (Lin, Cheng & Lawrenz, 2000; Nussbaum, 1985). Julien suggested that his students would draw the air molecules as “dots on the bottom of the flask, as if they had sunk”, as seen in the literature (Nussbaum, 1985; Novich & Nussbaum, 1981). Matthew said his students would draw an even distribution of air particles but all of the particles would be below the level of the flange on the flask (Nussbaum, 1985; Novich & Nussbaum, 1981). Matthew also offered additional alternate conceptions. He suggested that students might also draw a blank flask, as if nothing were in it; there might be more dots in the flask; and the dots might be clustered without equal distribution below the flange. Matthew was the only participant to do this. Sam stated that his students would draw the correct answer. When pressed for “incorrect” answers, Sam stated that his student might show the molecules of air
clustered around the flange where the air was pumped out. While this specific drawing is not evidenced in Nussbaum (1985), the idea of the air molecules clustered in a specific area of the flask is evidenced.

When asked about how they would address these alternate conceptions in their teaching, all of the participants stated that they would tell students the correct answer and then use logic to help the students see why the correct answer is correct. This approach to student alternate conceptions is not uncommon (Chick & Vincent, 2005). Erik and Julien gave specific examples of this logic. Both Erik and Julien used the classroom full of air as an example of how students do not need to get on the floor to get air into their lungs. The air in the room is everywhere—just like in the flask. While Matthew’s first impulse was to tell students the answer and use logic to explain the correct answer, he did suggest another pedagogical technique. He was the only participant to do this. Matthew suggested having students pretend to be gas molecules and act out gas particle motion in a confined area in the classroom.

The second scenario (see Appendix B) showed a cross-section of a steel tank full of hydrogen gas. The hydrogen molecules are drawn as dots in the tank. Again, participants were asked to predict what they think their students will draw for the hydrogen molecules in the cross-section when the tank is cooled.

All of the participants except Julien were concerned with how much the tank was cooled. Erik, Matthew and Sam mentioned that drawings of molecules on the bottom of the tank could be “correct” if the hydrogen gas has been cooled enough to support a phase change into liquid hydrogen. Aside from this issue, Erik, Julien and Matthew
suggested that their students would draw the gas molecules on the bottom of the tank, as if they had sunk (see Figure 5.11).

*Figure 5.11: Julien’s Example of Student Conceptions for the Second Scenario of the Written Assessment*

Sam stated that his students would draw the gas molecules as a cluster of dots in the middle of the tank (see Figure 5.12). Both student alternate conceptions the participants provided are seen as choices on the Chemical Concept Inventory and the Test about Particles in Gas (Novich & Nussbaum, 1981)

*Figure 5.12: Sam’s Example of Student Conceptions for the Second Scenario of the Written Assessment*

To address this student alternate conception in his classroom, again, all participants stated that they would tell their students the correct answer and use logic to explain the correct answer. Erik and Julien used a cold environment as an example. Erik selected an ice hockey rink and Julien chose a cold classroom. Both pretended to ask their students if the students would need to kneel to breathe the air.


Implications

During the interviews of the participants, it was difficult for the participants to suggest possible student alternate conceptions. In fact, Sam was so reluctant to provide student alternate conceptions that he was prompted numerous times beyond his fellow participants. While the participants eventually provided student alternate conceptions found in the literature, only one alternate conception was provided by three of the participants. This implies that those three participants may not know or understand the variety of student alternate conceptions their students hold. It also implies that the participants may not understand how student alternate conceptions impact their instruction (Gomez-Zwiep, 2008).

In addition to not knowing or understanding the student alternate conceptions themselves, the participants do not know or understand how to address those alternate conceptions in their curriculum and instruction. As Chick & Vincent (2005) found, the most common approach in dealing with alternate conceptions was to re-explain the material. All of the participants stated they would explain the concepts again, either through logic or analogy. While educational analogies have been suggested to confront student alternate conceptions (Klammer, 1998), alternate conceptions may survive many stages of instruction and even after instruction is complete (Nussbaum, 1985). The participants seem to lack a complete understanding of student alternate conceptions and how to address those conceptions in their classrooms.

Curriculum Planning

In analyzing the curricula of the participants, the questions of the role of the textbook and the criteria for selecting activities, experiments, demonstrations,
worksheets, etc. became important to address. Since the present study did not focus on the role of the text and selection criteria for specific activities, experiments, demonstrations and the like, only a brief discussion will follow.

Erik stated in the first interview that his curriculum is encased in three large three-ring binders his department provided for him. It was implied that Erik should follow the curriculum provided since students typically change instructors at the beginning of each trimester. The importance of each student being presented the identical content as well as ending instruction at the same place for each trimester was stressed. Erik stated that each unit begins with a packet and prior knowledge assessment based on reading the textbook and taking notes. It is not known from Erik’s interview how the curriculum was developed.

Julien stated in the first interview that his curriculum follows the textbook, Chemistry in the Community, explicitly. During the first interview, Julien referred only to the text showing every lesson as provided in the text. Julien deviated from the textbook only once, when he chose to substitute the copper ball with a pressure gauge attached in place of the oil-plugged capillary tube to illustrate Charles’ Law. Unfortunately for Julien, the copper ball apparatus does not illustrate Charles’ Law. It illustrates Gay-Lussac’s law where pressure changes in accordance with temperature changes.

The influences on Matthew and Sam’s curricula are unknown. Neither participant directly stated what resources they draw upon or how they select activities, demonstrations, experiments, etc. Yet, both Matthew and Sam select demonstrations that seem to misrepresent the phenomena they were trying to recreate (Geddis, 1993). Sam
chose the use of a vacuum pump to reduce pressure to show an increase in volume of a gas, not realizing that in doing so he is also changing the number of molecules in the system.

Conversely, Matthew chose a complex demonstration as a macroscopic representation of Charles’ Law placing some warm water in a large syringe and changing the pressure so that the water “boils”. However, a change in pressure and “temperature” in the syringe that allows the water to “boil” is not an illustration of Charles’ Law. It is an illustration of the Combined Gas Law, where pressure changes, resulting in a change in volume occupied by the air molecules trapped in the syringe, which allows for a “temperature” change. Matthew does not seem to recognize the complexity of the demonstration both in terms of the gas laws and connections to vapor pressure and surface tension related to boiling.

During the first interview, participants were asked if they had access to the apparatus presented in the scenarios, would they use it in their classrooms. In addition to using the apparatus, participants were also asked how and why they would use the apparatus. These data might provide insights into the influences that affect curriculum decisions.

Regarding the first apparatus with the oil reservoir and glass tube (see Appendix B), all of the participants stated that they would use the apparatus in class because students would actually be measuring pressure instead of using books or water as a proxy for pressure. All participants thought it was valuable for students to actually measure the pressure and volume variables from the apparatus and use those data to illustrate the relationship between pressure and volume. Here we see the influence of accurate
quantitative data collection outweigh the idea of students being able to “see” the pressure changing by adding books or water. The desire for accurate quantitative data collection may be more about the participants’ desire to fit the scientific explanation of the phenomena than having to “simplify” the phenomena in order for the students to understand the relationship between pressure and volume (Geddis, 1993). However, does using the apparatus without a macroscopic representation for pressure, such as books and water, inhibit the understanding for learners? Perhaps selecting the apparatus where the focus is on the particulate representation for pressure would also inhibit the understanding for learners since learners cannot “see” pressure increasing by adding books or water but must rely on the pressure gauge to indicate pressure is rising.

Regarding the second apparatus, the Erlenmeyer flask and tubing with the oil plug (see Appendix B), Erik, Julien and Sam stated that they would use the apparatus. All three participants cited the ability of students to easily mark the position of the oil drop in the apparatus for a specific temperature. Again, students would be directly measuring the changing variables, a feature that appealed to the three participants. Sam was very enthusiastic about the apparatus. The experiment he currently uses employs an oil-plugged capillary tube. The change in the placement of the oil plug is too small for accurate measurement by his students. He would like to use this apparatus because it is of larger scale and would allow for more accurate marking of the oil plug and thus would reduce the likelihood of error in his student’s results. In this example, Sam’s desire for more accurate quantitative data not only takes into account his students but also the accuracy of the data to illuminate the concept of absolute zero.
Summary

PCK is an amalgam of subject matter knowledge for teaching, pedagogical knowledge and knowledge about learners (Grossman, 1990; Gess-Newsome, 1999). In the present study, the data support the conclusion that the participants are lacking in all areas of PCK. The participants’ scores on the subject matter knowledge for teaching assessment were low indicating a superficial understanding of the kinetic molecular theory, Boyle’s law and Charles’ Law, particularly with particulate representations but surprisingly with symbolic representations as well. In addition, the participants exhibited alternate conceptions as students about the chemistry concepts targeted on the subject matter knowledge for teaching assessment similar to the alternate conceptions held by their students. The participants did not exhibit a conceptual understanding of the four different representations when asked to apply them in novel scenarios. In addition, the participants did not exhibit an ability to transfer from one representation to another as seen on the subject matter knowledge for teaching assessment.

When asked about alternate conceptions and how they would address them in their classrooms, the participants showed limited understanding of possible student alternate conceptions as exhibited in the literature. The participants also showed limited understanding of how to address those alternate conceptions. While both Erik and Julien suggested a chemical analogy, it was not used to confront and transform students’ alternate conceptions, rather to re-explain content.

Overall the data indicate that all of the participants have poor PCK for the Gas Laws. Subject matter knowledge for teaching is transformed by PCK into lesson plans so
that students can work with the content knowledge (Abell, 2007). Given the participants’
poor PCK for the Gas Laws, perhaps the participants qualify neither as content specialists
for Gas Laws nor as pedagogues (Shulman, 1987).
CHAPTER SIX
DISCUSSION AND IMPLICATIONS

Review of the Study Purpose

Recall from Chapter One the purpose of this study: to describe chemistry teachers’ knowledge of chemistry representations, student conceptions and subject matter knowledge for teaching the behaviors and properties of gases. It has been agreed upon in the literature that PCK is topic-specific (Bell et al, 1986; Abell, 2007) and that PCK includes understandings of the representations and student conceptions for a specific topic (Abell, 2007). Further studies of subject matter knowledge and PCK have been suggested (van Driel, Verloop, & de Vos, 1998; Daehler & Shinohara, 2001; Kinach, 2001; Wilson & Wineburg, 1993). An investigation of chemistry teachers’ knowledge of chemistry representations, student conceptions and subject matter knowledge for teaching regarding the Gas Laws, could also serve to describe teachers’ PCK for the Gas Laws.

Discussion

Research Question 1

The first research question asked, “What knowledge do chemistry teachers have of chemistry representations with respect to the behaviors and properties of gases?” This question was answered primarily through the representations targeted on the subject matter knowledge for teaching assessment (see Appendix B). Through the analysis of the representations targeted on the subject matter knowledge for teaching assessment, each participant’s ability to articulate each representation and transfer from one representation to another could be examined.
A secondary source of information on teachers’ knowledge of chemistry representations was analysis of their curricula. Through the analysis of each participant’s curriculum, the representations used by each participant in his curriculum were apparent (see Table 5.3). This can provide a glimpse into the participants’ PCK as applied to the subject matter knowledge for teaching the Gas Laws.

Representations of the Subject Matter Knowledge for Teaching Assessment

The primary method of investigating the participants’ knowledge of chemistry representations was through the administration of the subject matter knowledge for teaching assessment (see Appendix B). Each question corresponded to a specific representation or a number of representations that were to be used in answering the question (see Appendix D). By using the subject matter knowledge for teaching assessment and representations, it was possible to see how well each participant utilized the representation in answering the subject matter knowledge for teaching assessment questions as well as their ability to transfer between representations.

Macroscopic Representation

The macroscopic representation was the only representation successfully used by all of the participants (see Table 5.3). Each participant was able to predict with accuracy what would happen in each scenario of the subject matter knowledge for teaching assessment. This is to be expected based on the literature (Lin, Cheng, & Lawrenz, 2000).

There may also be a connection between the successful use of the macroscopic representation on the assessment and classroom practice. All of the participants used numerous demonstrations and a few experiments that focused on the macroscopic
representation to illustrate the behaviors and properties of gases. The macroscopic representation was used almost daily by all the participants as evidenced by the analysis of their curricula. For example, three of the four participants used a syringe with air trapped inside and books or water placed on the plunger to represent pressure pushing down on the plunger of the syringe to illustrate the relationship between pressure and volume of a gas, i.e. Boyle’s Law. Perhaps the frequent use of the macroscopic representation in the participants’ classrooms is tied to their success on the subject matter knowledge for teaching assessment for the macroscopic representation questions. Or the participants’ success on the macroscopic representation questions on the subject matter knowledge for teaching assessment is tied to the frequent use of the macroscopic representation for demonstrations and experiments in the participants’ curricula. Further investigation of any relationships between success on the subject matter knowledge for teaching assessment and classroom practice is warranted.

**Particulate Representation**

Use of the particulate representation was difficult for most of the participants as shown on the subject matter knowledge for teaching assessment (see Table 5.2). The literature supports this finding (Lin, Cheng, & Lawrenz, 2000; Gabel, 1998). The three questions on the assessment involving the particulate representation targeted the application of the kinetic molecular theory to explain the properties and behaviors of gases in a novel scenario. Since three of the four participants specifically taught the kinetic molecular theory in their curricula, it might be expected that they would have higher scores than the one participant who did not teach the kinetic molecular theory. This was not necessarily the case.
All of the participants displayed little understanding of the particulate representation when asked to apply the kinetic molecular theory to novel scenarios. It did not seem to matter if the particulate representation was never used in the participants’ curriculum, as was the case with Erik. Erik did not teach the kinetic molecular theory nor did he use the particulate representation in his teaching. Julien used the particulate representation almost daily in his teaching but also did not score well on the subject matter knowledge for teaching assessment for the particulate representation. Matthew and Sam only used the particulate representation at the beginning of their units on the gas laws when they directly taught the kinetic molecular theory. The particulate representation did not make an appearance again in Sam’s teaching and Matthew only used the particulate representation again on the unit test for an essay question about the kinetic molecular theory.

In addition to the superficial understanding of the participants for the particulate representation, the participants were not able to transfer from the macroscopic representation, used frequently in their curricula and successfully on the subject matter knowledge for teaching assessment, to the particulate representation to explain the novel scenarios. There appeared to be a disconnection between the macroscopic representation and using the particulate representation to explain the observable phenomena in the novel scenarios. The participants in this study appear to have similar difficulty transferring between the macroscopic and particulate representations, as do students, as documented in the literature (Van Driel, de Jong & Verloop, 2002; Gabel, 1998; Nakhleh, 1992; Bodner, 1991; Kozma & Russell, 1997) and specifically for the behavior and properties of gases (Cetin, Kaya, & Geban, 2009). Perhaps the participants’ lack of display of
transfer between the macroscopic representation and the particulate representation is connected to their classroom practices of not asking students to transfer between the macroscopic and particulate representations also.

**Symbolic Representation**

On the subject matter knowledge for teaching assessment, the symbolic representation (see Table 5.2) participants’ scores were low, except for Sam. Sam received higher scores than his fellow participants, thus displaying greater proficiency at applying the symbolic representation to novel scenarios. However, the symbolic representation used in the participants’ curricula was essentially given three variables of on the symbolic forms of the gas laws, find the fourth. For example, given $P_1$, $V_1$ and $V_2$, find $P_2$ using Boyle’s Law, $P_1V_1 = P_2V_2$. The problems given in the participants’ curricula were isolated and devoid of context. The problems did not tie into demonstrations or experiments conducted in the classroom. Neither was the symbolic representation used to connect concepts between the macroscopic and particulate representations. The symbolic representation was used in isolation for the participants.

On the surface, these data seem to imply that while the symbolic representation is used widely in all of the participants’ curricula, only Sam seems to have a more sophisticated understanding of the symbolic representation since he consistently received higher scores. As in the particulate representation discussion, these data seem to imply that use of the representations in a participant’s curriculum does not correspond with conceptual understanding of that representation when applied to novel situations (Bodner & Domin, 2000; Nakhleh, 1993; Niaz & Robinson, 1992). The use of a representation does not necessarily correspond with conceptual understanding of that representation is
shown in this study. The novel scenarios presented to the participants required the participants to recognize the properties and behaviors of gases in a novel context and how to appropriately apply the knowledge to the novel scenario. This is a much higher order thinking skill than using the symbolic representation of a gas law and solve for an unknown variable given the rest of the variables in the gas law.

*Graphic Representation*

The graphic representation was targeted by two questions on the subject matter knowledge for teaching assessment (see Appendix B). Question 2e and question 3e asked participants to provide a graph of data collected in previous questions for two novel scenarios (see Table 5.2). Because Matthew does not use the graphic representation in his curriculum at all, it is to be expected that Matthew would not score well on the graphic representation questions. That was the case. Matthew scored 0/3 on both graphic representation questions. Perhaps Matthew does not teach what he does not understand.

Since both Julien and Sam use the graphic representation more frequently than do the other participants, it is expected that they would score the highest on the graphic representation questions (see Table 5.2). That was the case with Sam but not with Julien. Julien failed to correctly answer question 3e, such that he received a score of 0/3. While Julien uses the graphic representation frequently in his curriculum, he seems to struggle with the graphic representation in novel scenarios as presented on the subject matter knowledge for teaching assessment.

Another unexpected result, the inverse of Julien’s difficulty, was Erik’s apparent thorough understanding of the graphic representation. Erik used the graphic representation only once in his unit on the Gas Laws. However, Erik’s scores were
identical to Sam’s, indicating that Erik had a firm grasp of the graphic representation even though he did not use the graphic representation in his curriculum. There appears to be more to curriculum and instruction decisions than what Erik knows and understands about representations and the gas laws.

Transfer Among Representations

In addition to investigating the participants’ knowledge of representations, the ability to transfer between representations was also analyzed. The data show that three of the four participants were not able to transfer between representations. We see that only the macroscopic representation was successfully employed on the questions that targeted the macroscopic representation. Sam’s data show that he was more flexible with transferring between representations. With regard to the other three representations, the particulate, symbolic and graphic representations, it appears that Sam is the only participant who is adept at utilizing the different representations in novel scenarios and is able to transfer successfully between representations in novel scenarios. The ability to transfer between representations is crucial to developing a deep conceptual understanding of chemistry (Kozma & Russell, 1997; Bodner & Domin, 2000). The inability of the participants to demonstrate representational competence (Kozma & Russell, 1997) indicates that the participants do not have a conceptual understanding of the Gas Laws.

Curriculum

Recall, a secondary source of information on teachers’ knowledge of chemistry representations was analysis of their curricula. Through the analysis of each participant’s unit and lesson plans, demonstrations, experiments, assignments, notes, etc., the representations the participant used in their curriculum was apparent (see Table 5.3).
Erik, his curriculum was prepared for him from his department, which relied on the textbook. Julien also used his textbook as his source of curriculum. Both Matthew and Sam created their own curricula from a variety of sources, such as the textbook, the Internet, colleagues and conferences. This can provide a glimpse into the participants’ PCK as applied to the subject matter knowledge for teaching of the Gas Laws.

**Macroscopic and Symbolic Representations**

As stated in Chapters Four and Five, the predominant representations that appeared in all of the participants’ curricula were the macroscopic and symbolic representations (see Table 5.3). Similar findings were found in previous studies of chemistry teachers’ classroom practices (Niaz & Robinson, 1992; Nakhleh, 1993). Participants used classroom demonstrations to illustrate macroscopic observations about the Gas Laws. Without using the particulate representation or the symbolic representation to explain what was observed during the demonstration, students were subsequently asked to use the symbolic representation of the Laws, such as $P_1V_1 = P_2V_2$ in an unrelated worksheet or problem set from the textbook. It appears from the curricula analysis that students are expected to perform the mathematics of the symbolic representation and did not ask their students for a conceptual understanding of the Gas Laws. However, students often do not readily make connections from the symbolic representation to other representations to develop a more conceptual understanding (Bodner & Domin, 2000; Nakhleh, 1993; Gabel, 1998; Kozma & Russell, 1997; van Driel, de Jong & Verloop, 2002).
Particulate Representation

The particulate representation was used only for the instruction of the kinetic molecular theory (see Table 5.3). One participant never taught the kinetic molecular theory and never used the particulate representation. Two of the three who did teach the kinetic molecular theory used the particulate representation only during that instruction. Once the theory had been taught, at the beginning of the unit on Gas Laws, the particulate representation was not seen again. To understand the macroscopic and symbolic representations, the particulate nature of matter must be understood (Gabel, 1998). Without teaching the particulate representation at all or presenting the particulate representation only once during the unit on Gas Laws, students develop only the surface features of a single representation, the symbolic representation, and thus do not connect other representations to underlying principles and concepts (Kozma & Russell, 1997).

Graphic Representation

The same can be said for the graphic representation (see Table 5.3). One participant never used the graphic representation in his instruction. Another participant used the graphic representation only once. The remaining two participants used the graphic representation twice in their instruction. While the graphic representation does not always apply to every topic taught in the Gas Laws, the Gas Laws do lend themselves to frequent use of the graphic representation.

Worthy of note is Julien; his curriculum was noticeably different from that of his fellow participants (see Table 5.2). Julien’s curriculum, laid out by the American Chemical Society, can be found in the textbook, Chemistry in the Community. Julien
rigorously follows the curriculum with only slight deviation. Julien’s curriculum utilized multiple representations frequently is his instruction. For example, when teaching Charles’ Law over a two-day period, Julien’s text used the macroscopic, particulate and graphic representations twice and the symbolic representation once. His fellow participants, Erik and Matthew, teaching Charles’ Law on one day, used only the macroscopic and symbolic representations. Sam taught Charles’ Law over a two-day period, as did Julien, but focused on the macroscopic and symbolic representations, twice each day, with one use of the graphic representation. Julien’s curriculum was the only curriculum that consistently used the particulate and graphic representations in conjunction with the macroscopic and symbolic representations. The three other participants focused primarily on the macroscopic and symbolic representations in their curriculum.

Summary

In answering the research question: what knowledge do chemistry teachers have of chemistry representations with respect to the behaviors and properties of gases, a two-fold response seems necessary. The participants seem to have a superficial understanding of the particulate, symbolic, and graphic representations, and they are not able to transfer from one representation to another. This indicates both a lack of conceptual understanding of the representations regarding the Gas Laws and also of the subject matter knowledge for teaching regarding the Gas Laws. However, all of the participants’ curricula employed at least two different representations. It appears that the participants are not intentionally planning their lessons for the use of different representations and the development of representational competence.
Referring to the second interview, Erik and Julien chose to follow a prescribed curriculum. Erik follows the curriculum that the science department in his school has prepared for him. This curriculum tends to follow the text, Chemistry by Prentice Hall (2002). Julien’s text is Chemistry in the Community by the American Chemical Society (2002); he follows it with high fidelity. Thus, Erik and Julien’s curricula and consequently the representations they use are based entirely on their textbooks.

Matthew and Sam chose to follow their own ideas of curriculum. While both Matthew and Sam have textbooks, Modern Chemistry by Holt, Rinehart, and Winston (2002) and Chemistry by Addison-Wesley (2002), the texts serve more as a supplementary resource for their curricula rather than as a foundation. Both Matthew and Sam spend considerable time searching the Internet, old files, and other resources for new demonstrations, PowerPoint slides, experiments, simulations, movies and film clips to add to their curricula. Sam has considerably more to draw on, as he has saved a great deal of material acquired during the forty years of his teaching career. However, this buffet-style of curriculum building may lead to the omission of representations. For example, Matthew does not use the graphic representation in his curriculum. Sam uses the particulate representation only when teaching the kinetic molecular theory and never uses it again in his unit on the Gas Laws.

Research Question 2

This question asked what understandings do chemistry teachers have of student conceptions with respect to the behaviors and properties of gases? This question was addressed directly by asking the participants to respond to novel scenarios and provide answers they think their students would provide. After providing student conceptions,
the participants were asked directly how they would address these conceptions in their classroom (see Appendix C).

**Student Conceptions**

All of the participants were able to provide one student alternate conception to the two scenarios presented in the first interview (see Appendix C). Only Matthew offered more than one student alternate conception for the first scenario. For the first scenario, all of the participants presented different student alternate conceptions. However, Sam offered student alternate conceptions only after being pressed. He initially stated that, “most of the students would show the correct idea.” Sam may think that his students do not have alternate conceptions.

For the second scenario, all of the participants except Sam provided the same student alternate conception. However, in the second scenario, the cooling of hydrogen gas in a steel tank, three of the four participants were very concerned with how cold the tank was cooled. If the tank was cooled such that a phase change to liquid hydrogen occurred, and if a student drew dots representing the hydrogen molecules clustered at the bottom of the tank, that drawing would be correct and thus not an alternate conception. This concern for the temperature implies that these three participants do not understand student alternate conceptions.

The lack of student alternate conceptions provided by the participants implies that the participants have a poor understanding of student conceptions of the behaviors and properties of gases. In addition to the debate about the temperature for the second scenario, it seems that all of the participants are limited in their understanding of student alternate conceptions.
Changing Student Conceptions

When asked in both scenarios how they would address student alternate conceptions, all of the participants suggested that they would talk their students through the correct answer using logic. Using the second scenario of the hydrogen gas being cooled in a steel tank as an example, Erik stated that a possible student alternate conception would be to have the hydrogen molecules clustered near the bottom of the tank, as if they had sunk. To address this alternate conception, Erik suggested that he would ask students about being somewhere cold and asking if they had to kneel to get at the air molecules when breathing. Julien suggested something similar when asked how he would address the same student alternate conception. Educational analogies have been suggested as a method for challenging alternate conceptions (Klammer, 1998). However, alternate conceptions may survive many stages of instruction and even after instruction is complete (Nussbaum, 1985). Thus, the one time use of an educational analogy by Erik and Julien will not yield change in students’ alternate conceptions.

Matthew is the only participant who suggested pedagogy aside from lecture to address student alternate conceptions. As a way of using logic, Matthew suggested that students might act out the motion of gas molecules in a confined space in the classroom. Matthew’s idea was that students naturally without direction would spread out creating space between them to show that gas molecules in a container behave the same way. This “acting out” the motion of molecules is still using logic to address student alternate conceptions. Matthew’s kinesthetic example of students acting as gas molecules is an educational analogy and suggested in the literature as pedagogy to challenging student alternate conceptions (Klammer, 1998). The one time use of the analogy will not change
students’ alternate conceptions as alternate conceptions have been shown to survive instruction (Nussbaum, 1985).

It seems clear from these data that none of the participants understand how to address student alternate conceptions other than to re-teach the material (Chick & Vincent, 2005; Bodner 1992). None of the participants mentioned any other pedagogical knowledge or pedagogical content knowledge for addressing student alternate conceptions. Obviously, these participants’ understanding of student alternate conceptions and how to challenge student alternate conceptions in the classroom are lacking.

**Summary**

From these data, it seems that all of the participants have a poor understanding of student alternate conceptions, especially how to address them in their classrooms. Only Matthew suggested more than one alternate conception for the first scenario and suggested students act out the motion of gas molecules to address student alternate conceptions of the behaviors and properties of gases. However, none of the participants’ curricula incorporated explicit discussion of prior knowledge, discrepant events, development of a range of conceptual schemes or using ideas in a range of scenarios (Driver, Guesne, & Tiberghien, 1985). Thus, the understandings the participants have of student conceptions with respect to the behaviors and properties of gases are poor and limited.

**Research Question 3**

This question asked what is the subject matter knowledge for teaching that chemistry teachers have regarding the behaviors and properties of gases? This question
was addressed by the subject matter knowledge for teaching assessment (see Appendix B).

Kinetic molecular theory

Three questions on the subject matter knowledge for teaching assessment addressed the kinetic molecular theory. Questions 1a and 1b (see Appendix D and Table 5.2) addressed the theory directly. Question 2b addressed the theory in a novel scenario. Based on the scores each participant received on the subject matter knowledge for teaching assessment, Julien and Sam seem to understand the kinetic molecular theory in isolation. However, none of the participants seem to fully understand the kinetic molecular theory when applied to a novel scenario.

In addition, there were a number of alternate conceptions held by the participants. Both Julien and Sam said that gravity would impact the CO$_2$ molecules in the flask such that they would stay mostly toward the bottom of the flask. Another alternate conception, presented by both Erik and Matthew, focused on the two gases having the same kinetic energy. A third alternate conception of the molecules’ motion in the flask, proposed by Erik, suggests that the different shapes of the molecules would impact the rotation of the molecules. Erik states that because the carbon dioxide molecules are of a bent shape, their different rotations would then impact the momentum of each molecule.

These alternate conceptions are not mentioned in the literature of student alternate conceptions (Nussbaum, 1985; Robinson & Nurrenbern; Novich & Nussbaum, 1978, 1981; Lin, Cheng & Lawrenz, 2000) or teacher alternate conceptions (Lin, Cheng & Lawrenz, 2000; Kruse & Roehrig, 2005). It appears that the alternate conceptions the participants hold are new to the research base.
The presence of the participants’ alternate conceptions and lack of knowledge about the kinetic molecular theory implies that Erik and Matthew have a naive understanding of the kinetic molecular theory while Julien’s and Sam’s understanding is slightly more sophisticated. Yet, none of the participants seem to be able to use the kinetic molecular theory in a novel scenario, which implies limited understanding of the kinetic molecular theory.

*Boyle’s Law*

Question 2a (see Table 5.2 and Appendix B) targeted the macroscopic representation of identifying pressure and volume differences in a novel scenario. All of the participants received a score of 3/3 for this question. This implies that all of the participants could identify pressure and volume differences.

However many other parts of the application of Boyle’s Law were not correct. For example, the two-system problem highlighted that the participants could not figure out that pressure had to equalize, exposing their superficial understanding of Boyle’s Law. Also, Sam talked about surface area and force as pressure for the oil trapped in the reservoir; he does not see the reservoir linked to the glass tube. Additionally, Matthew grabbed the Ideal Gas Law and began crossing out variables in such a manner as to give the impression that he was hammering this equation to fit his conceptions. This behavior is similar to students. Teachers and students have similar alternate conceptions and superficial understandings the Gas Laws.

*Charles’ Law*

Question 3a (see Table 5.2 and Appendix B) targeted the macroscopic representation of predicting changes in the volume of gas in a novel scenario. All of the
participants received a score of 3/3 for this question, demonstrating a high degree of competence in this limited area.

Similarly, this problem required the realization that the pressure inside the apparatus had to equalize with the pressure outside the apparatus. The participants were unable to do that. If participants did not realize pressure equalized and became constant, they would select the incorrect variables to measure and/or graph. That is exactly what happened for the participants. Again, the participants exhibited a superficial understanding of Charles’ Law and had similar alternate conceptions as that of students.

Implications

The participants selected for this study each hold a degree in chemistry, had been teaching in a high school for three or more years and had taught a unit on the gas laws in the 2008-2009 school year. These participants are termed “highly qualified.” (No Child Left Behind).

Representations

Representations Teachers Use Themselves

The data presented in this study suggest that the four participants do not have a conceptual understanding of the particulate, symbolic, and graphic representations and are not adept at transferring from representation to representation when presented with novel scenarios. The researcher does not think that the four participants are unique (Nakhleh, 1992; Kozma & Russell, 1997). Teachers themselves must have a conceptual understanding of each representation and must be adept at transferring representations in teaching chemistry if they expect their students to do it (Bodner & Domin, 2000; Lin, Cheng & Lawrenz, 2000).
Before modeling for students the use of multiple representations, teachers must have a conceptual understanding of each representation including the use and limitations of each representation. For example, when using the symbolic representation of the gas laws, the symbolic representation is limited to predicting initial and final states of the gas laws. Thus, when instructing students about the symbolic representation for Boyle’s Law, teachers should understand and teach their students that the Boyle’s Law has limitations. When limitations of representations are not understood, difficulty occurs.

For example, Julien tried to utilize the symbolic representation to explain what was happening to the gas molecules trapped in the reservoir and glass tube during a change in pressure for the second scenario on the subject matter knowledge for teaching assessment (see Appendix B). In using the symbolic representation beyond its limits, Julien displayed confusion about the scenario.

Another example might be applying macroscopic qualities to the particulate representation. Both Julien and Sam applied the macroscopic quality of gravity to individual gas molecules in the first scenario of heating equal amounts of carbon dioxide and oxygen in a flask. The particulate representation for gases is limited to the principles of the kinetic molecular theory. Stating that gravity will cause the heavier carbon dioxide molecules to remain near the bottom of the flask is going beyond the limits of the particulate representation.

Representations in Curricula

The participants in this study do not intentionally plan for the use representations and development of representational competence in their curricula. The different representations that appeared in Erik and Julien’s curricula were a result of the textbook
being written with the use of different representations. Only Julien’s curriculum repeatedly used the macroscopic, particulate, symbolic, and graphic representations for most of the topics in his unit on the Gas Laws. This may be a product of Julien’s rigorous adherence to his textbook, Chemistry in the Community. This text provides all four representations in most of the activities, experiments and question sections Julien uses as his curriculum. While Julien’s text provided frequent use of all four representations, Julien did not demonstrate conceptual understanding of the particulate, symbolic, and graphic representations or representational competence beyond his fellow participants. Thus, using a textbook full of multiple representations for a number of years did not provide Julien with representational competence.

In recent years, texts and supplementary materials for chemistry have included all four representations in all topics. This may be due to the literature reinforcing the use of multiple representations can provide a conceptual understanding (Gabel, 1998; van Driel, de Jong & Verloop, 2002; Bodner & Domin, 2000; Kozma & Russell, 1997; Levy, 2009) in chemistry. However, all texts used by participants in this study were published in 2002. All four representations may still not be present in texts and supplementary materials or emphasized on common standardized assessments.

However, regardless of representations in textbooks, teachers do not intentionally plan for the representations they presented to their students. If teachers do not have a conceptual understanding of representations, they will not ask their students to have a conceptual understanding. For example, if teachers are not comfortable with or understand the particulate representation they will not present that representation to their students or present it in a superficial manner. This also applies to representational
competence. In order to model to students the use of multiple representations to explain chemical phenomena, teachers themselves must be able to transfer from representation to representation as well. If teachers do not have representational competence, they will not ask their students to have it either.

Student Conceptions

As discussed earlier in this chapter as well as Chapters Four and Five, the four participants in this study have a naïve and limited understanding of students’ alternate conceptions regarding the behaviors and properties of gases, and how to address these conceptions in their classrooms. While teachers can teach most of their careers unaware of students’ alternate conceptions or how to address them in classrooms, citing Sam as an example of a teacher of forty years’ experience, to ignore them results in limited understanding of learners and thus limited PCK.

Thus, understanding student alternate conceptions and how to address them in classrooms would be of benefit both to the profession of teaching as well as to the students. It seems logical that if a teacher knows what alternate conceptions students hold, curriculum and instruction can be designed to target those alternate conceptions in a purposeful manner. One method of determining student alternate conceptions and challenging them is through formative assessment. Formative assessment can be used daily in the classroom to determine what students understand, what alternate conceptions do they hold and what the next unit of instruction should entail. Again, here we see a bimodal model for generating and testing explanations that can lead to the assessment and challenge of student alternate conceptions.
Developing Conceptual Understanding of Representations, Representational Competence, and Student Alternate Conceptions

If employment of all four representations throughout curricula and identifying and challenging student alternate conceptions is to be achieved, teachers should understand the importance of using multiple representations, particularly the particulate representation when teaching any chemistry topic, possess representational competence, and understand student alternate conceptions and how to challenge them. The current model of teaching and learning representational competence and addressing student alternate conceptions is one-way: teacher shows and student may or may not make connections. Shifting from a one-way model into a bimodal model where teacher and student are interacting with one another to generate and test explanations may be beneficial. There are many entry points where development of conceptual understanding of representations, representational competence, and student alternate conceptions can be achieved for chemistry teachers.

Obviously, the first entry point for developing conceptual understanding of representations, representational competence, and alternate conceptions could be college chemistry courses. While college chemistry courses are populated with the symbolic representations, Bodner (1991) and Bodner & Domin (2000) strongly advocate for multiple representations to be present in college chemistry classrooms. Chemistry professors are adept at using representations and transferring between representations (Bodner & Domin, 2000). In addition, through the discussion and instruction of representations and chemistry content knowledge, alternate conceptions can also be addressed. A college chemistry classroom seems like an ideal environment for not only
learning chemistry content, but also developing conceptual understanding of representations and representational competence and challenging alternate representations. Future chemistry teachers can then apply a conceptual understanding of representations and representational competence to the classroom.

A second point of entry for developing conceptual understanding of representations, representational competence, and student alternate conceptions is in initial licensure programs and student teaching. A conceptual understanding of representations, representational competence, and student alternate conceptions, as part of pedagogical content knowledge, could be developed as pre-service teachers and student teachers learn lesson writing and development, pedagogical knowledge, enhance subject matter knowledge for teaching, and during instruction regarding learners, such as educational psychology and special education course work. Cooperating teachers and student teacher supervisors could mentor pre-service teachers in lesson development incorporating representations, representational competence, and targeting student alternate conceptions for the student teacher as well as his or her students.

For the practicing teacher, a point of entry for developing conceptual understanding of representations, representational competence and student alternate conceptions is professional development. The development of teachers’ own knowledge through extensive subject matter knowledge for teaching professional development increased competence regarding representation, explanation and communication (Hill & Ball, 2009). A bimodal model of interaction of testing and generating explanations improves subject matter knowledge for teaching, representational competence, explanation and communication. Targeting student alternate conceptions could also be
addressed through extensive subject matter knowledge for teaching professional development. Hill & Ball (2009) might be a model for professional development.

For example, college and university faculty in the chemistry and curriculum and instruction departments could provide workshops and summer courses focusing on representations and alternate conceptions to practicing teachers. Online communities for professional development for developing representational competence and targeting student alternate conceptions could be started and maintained. Professional Learning Communities and In-service/Curriculum days at individual schools could also provide for an environment for the development of conceptual understanding of representations, representational competence, and student alternate conceptions through the study of specific subject matter knowledge for teaching. Regardless of the environment chosen for professional development, extensive subject matter knowledge for teaching topics through a bimodal model where explanations are being generated and tested should be the avenue through which development of a conceptual understanding of representations, representational competence, and student alternate conceptions.

Curriculum resources are another point of entry for the development of conceptual understanding of representations, representational competence, and student alternate conceptions. Many recently published textbooks include the four representations discussed in this study. In addition to including the four representations, texts could also include in the resources for teachers as well as students, the limitations of representations, discussion and scaffolding of transferring between representations as well as providing multiple representations for the same concept. Student alternate
conceptions as well as activities that challenge student alternate conceptions could also be provided in teacher resources and material.

For example, Hill and Ball (2009) describe a mathematics lesson to teach students to subtract negative integers. The text the teacher being studied was using provided red and black chips to represent positive and negative numbers. At one point, the representation of the red and black chips did not work with the problem given. No explanation was given to inform the teacher as to how to proceed nor was a different representation, such as a number line, provided to present to students. While this is a mathematics example, this is not an isolated incident. The use of representations in textbooks is also superficial, without discussion of limitations of representations or offering of additional representations for the teacher. Textbooks and supplementary materials could be developed to better support teachers in the classroom (Hill & Ball, 2009).

Subject Matter Knowledge for Teaching

Employment as a teacher is not, in itself, an accurate indicator of that person’s depth of understanding of his or her area of instruction, as was shown in the subject matter knowledge for teaching assessment. While the four participants may understand the kinetic molecular theory, Boyle’s and Charles’ Law in their own curricula and instruction, Erik’s, Julien’s, and Matthew’s understandings are naïve and limited based on the novel scenarios presented in the assessment. Sam appeared to have more sophisticated understandings of the kinetic molecular theory and Boyle’s and Charles’ Laws, as shown in the scores received on the assessment.
This implies that three of the four participants have a limited understanding of the kinetic molecular theory, Boyle’s and Charles’ Laws. This does not bode well for chemistry classrooms. If the chemistry teacher does not thoroughly understand the subject matter knowledge for teaching, students are not going to gain a thorough understanding of the subject matter knowledge either. Teachers should receive professional development in their subject matter knowledge for teaching area. Since subject matter knowledge for teaching impacts PCK, improved subject matter knowledge for teaching also improves PCK.

Future Research

Only four participants were studied. To form general principles based on such a limited study is risky at best. It would be of benefit to conduct this same study with a larger sample. More participants would lead to greater richness in describing the knowledge chemistry teachers have of chemistry representations, student conceptions and subject matter knowledge for teaching. In addition, patterns may emerge in a larger sample that was hidden due to this study’s small sample size.

For example, in this study, it was not possible to tie representations used in the classroom to the representations targeted on the subject matter knowledge for teaching assessment. Perhaps with a larger sample size, patterns may emerge to confirm or dispute any connection between representations used in curricula and representations used by teachers themselves when presented with novel scenarios.

Observing in classrooms would also lend more data and richness to describing the knowledge chemistry teachers have of chemistry representations, student conceptions and subject matter knowledge for teaching. While PCK and teaching can be discussed in the
abstract, both are dynamic processes and need to be observed in action. By observing teachers interacting with students, the analogies, illustrations, examples, explanations, and demonstrations (Shulman, 1986) that allow students to make sense of chemistry, essentially PCK, can be observed and documented.

A third area for future research would be studying other topics in chemistry. PCK is topic specific (Bell et al, 1998). In order to understand teachers’ PCK, PCK of specific topics should be investigated. While the Gas Laws lend themselves well to the four representations of macroscopic, particulate, symbolic, and graphic, other topics in chemistry are of interest as well. Solutions, Acids and Bases, Chemical Equilibrium, and Chemical Reaction Energy and Kinetics are typically taught in high school chemistry and would lend themselves well to the four representations. Describing the knowledge chemistry teachers have of representations, student conceptions and subject matter knowledge for teaching for different topics in chemistry would be of benefit in understanding teachers’ PCK as a whole.
REFERENCES


Conference of the International Group for the Psychology of Mathematics

Education, Volume 2, (pp.249-256). Melbourne: PME.


U.S. Department of Education. *Race to the Top*.


## Appendix A

### The Gas Law PCK Model: The Intersection of Pedagogical Content Knowledge and Subject Matter Knowledge for Teaching Model

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<td>Macroscopic</td>
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<tr>
<td>Symbolic</td>
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<tr>
<td>Graphic</td>
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</table>
Kinetic Molecular Theory:
KM theory of gases is a theoretical model constructed to account for ideal gas behavior. This model assumes…

1. that the volume of the gas particles is zero,
2. there are no interactions between particles, and the
3. particles are in constant motion, colliding with the container walls to produce pressure.
4. In addition this model shows that the average kinetic energy of the gas particles is directly proportional to the Kelvin temperature of the gas. (Zumdahl).

<table>
<thead>
<tr>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening perfume and asking students to raise hands when they smell it. (Holt, b)</td>
<td>Picture of bottle with drawing of diatomic molecules moving in straight lines and colliding with walls of container. (Holt, b)</td>
<td></td>
<td></td>
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<tr>
<td>Gas molecules in a glass bottle with a screw top. Shows particulate model of gas molecules moving. (Holt, a)</td>
<td></td>
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</tbody>
</table>
Boyles’ Law: The volume of a given sample of gas at constant temperature varies inversely with the pressure. (Zumdahl).
The volume of a given amount of gas held at a constant temperature varies inversely with the pressure. (Glencoe).

<table>
<thead>
<tr>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syringe/book lab</td>
<td>When volume increases, the gas particles hitting any section of the wall in a given time decreases and the pressure decreases. (Active Chem.)</td>
<td>$V = \text{constant } \times \frac{1}{P}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Some Pressure</td>
<td>OR</td>
<td></td>
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<tr>
<td></td>
<td>2x pressure</td>
<td>PV = constant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Some Volume</td>
<td>OR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\frac{1}{2}$ volume</td>
<td>$P_1V_1 = P_2V_2$</td>
<td></td>
</tr>
</tbody>
</table>
Charles’ Law: The volume of a given sample of gas at constant pressure is directly proportional to the temperature in Kelvins. (Zumdahl)
The volume of a given mass of gas is directly proportional to its Kelvin temperature at constant pressure. (Glencoe)

<table>
<thead>
<tr>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air filled balloons dipped in liquid nitrogen contract and then expand again upon warming. (Holt text).</td>
<td>This property is explained by KM theory—at a higher temp, gas particles move faster, striking each other and the walls of their container more frequently and with greater force. For the pressure to stay constant, volume must increase so that the particles have farther to travel before striking the walls. Having to travel farther decreases the frequency with which the particles strike the walls of the container. (Glencoe).</td>
<td>( \frac{V_1}{T_1} = \text{constant} ) OR ( \frac{V_1}{T_1} = \frac{V_2}{T_2} )</td>
<td>![Graph showing the relationship between volume and temperature]</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Low Temp.</th>
<th>High Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small volume</td>
<td>Larger volume</td>
</tr>
</tbody>
</table>
Gay-Lussac’s Law: The pressure of a given mass of gas varies directly with the Kelvin temperature when the volume remains constant. (Glencoe).

<table>
<thead>
<tr>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure cooker (Glencoe)</td>
<td>Pressure is the result of collisions between gas particles and the walls of their container. An increase in temperature increases collision frequency and energy, so raising the temperature should also raise the pressure if the volume is constant. (Glencoe)</td>
<td>At constant volume, ( \frac{P_1}{T_1} = \frac{P_2}{T_2} )</td>
<td><img src="https://example.com/graph.png" alt="Graph" /></td>
</tr>
<tr>
<td>Some 2x temp.</td>
<td>Some 2x pressure</td>
<td></td>
<td>P</td>
</tr>
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<td></td>
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<td></td>
<td>T</td>
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</table>
Avogadro’s Law: Equal volumes of gases at the same temperature and pressure contain the same number of particles. (Zumdahl). Equal volumes of gases at the same temperature and pressure contain equal numbers of particles. (Glencoe).

<table>
<thead>
<tr>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>According to the KM theory, the particles in a gas sample are usually far enough apart that size has a negligible influence on the volume occupied by a fixed number of particles.</td>
<td>Gas volume is directly proportional to the number of moles of gas at the same temperature and pressure. $V=kn$.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylinders of gas under pressure. Volume of 1000 large Kr atoms = volume of 1000 small He atoms (Glencoe)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Combined Gas Law: The combined gas law expresses the relationship between pressure, volume and temperature of a fixed amount of gas. (Holt, b)

<table>
<thead>
<tr>
<th>Macroscopic</th>
<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot air balloon with explanation of which variables change as balloon fills on the ground as well as up in the air. (Glencoe)</td>
<td></td>
<td>(\frac{PV}{T} = k) [\text{OR}] (\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2})</td>
<td></td>
</tr>
</tbody>
</table>
Ideal Gas Law: An equation of state for a gas, where the state of the gas is its condition at a given time; expressed by \(PV=nRT\), where \(P\) = pressure, \(V\) = volume, \(n\) = moles of the gas, \(R\) = the universal gas constant, and \(T\) = absolute temperature. This equation expresses behavior approached by real gases at high \(T\) and low \(P\). (Zumdahl).

Describes the physical behavior of an ideal gas in terms of pressure, volume, temperature and number of moles of gas present. (Glencoe).

<table>
<thead>
<tr>
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<th>Particulate</th>
<th>Symbolic</th>
<th>Graphic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q re: how many times a CO(_2) cartridge can shoot a dart. (Active Chem.)</td>
<td>How did the number of magnesium atoms impact the number of molecules of hydrogen produced? (Active Chem.)</td>
<td>(PV = \text{constant}\nT) OR (PV = nRT)</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

Teachers’ Understanding of the Behaviors and Properties of Gases

This is an instrument developed to assess your understanding of the behavior and properties of gases. Results will be used only for research purposes. Please read each scenario carefully and respond to each question as best as you can. Take as much time as you wish for each question. Please do not consult any resources. Gas law formulas have been provided for you below. Thank you for your participation in this study.

\[ P_1V_1 = P_2V_2 \quad (T \text{ is constant}) \]

\[ \frac{V_1}{V_2} = \frac{T_1}{T_2} \quad (P \text{ is constant}) \]

\[ \frac{P_1}{T_1} = \frac{P_2}{T_2} \quad (V \text{ is constant}) \]

\[ \frac{PV_1}{T_1} = \frac{PV_2}{T_2} \]

\[ PV = nRT \quad (R = 0.0821 \frac{L \cdot \text{atm}}{\text{mol} \cdot \text{K}}) \]
1. The Erlenmeyer flask in the diagram below was evacuated and filled with equal amounts of oxygen and carbon dioxide at room temperature. The flask was then stoppered. Describe and/or draw the motion of the particles in the flask. Explain your reasoning.

b. If a burner is put under the flask and kept burning for a few seconds, describe and/or draw the motion of particles in the flask? Explain your reasoning.
2a. Using the diagram below, predict what will happen to the level of oil in the glass tube as air is added from the pump in the right of the diagram.

b. Using words and/or drawings, explain what is happening to the air particles in the reservoir and the glass tube before and after the air is added.

c. What data would you collect to know where the volume of trapped air in the glass tube would be for any given pressure?

d. How would you collect that data?

e. What would you plot if you were to graph the data?
3. An Erlenmeyer flask is closed with a stopper connected to a glass tube. A drop of oil, as shown in Figure 3, seals the glass tube. We move the whole apparatus in the diagram from a room with a temperature of 26°C (299 K) to an outdoor yard with a temperature of 5°C (278 K).

   [Diagram of an Erlenmeyer flask with a glass tube and a stopper]

   a. Predict what direction the oil plug will move or if it will remain motionless?

   b. Explain your prediction using words and/or drawings.

   c. What data would you collect to know where the oil drop would be when the apparatus is in a room at 120°C (393 K)?

   d. How would you collect that data?

   e. What would you plot if you were to graph the data?
Part B

5. The Tasks shown below were given to a number of students.

Read the story in drawings A, B and C above. As you may know, a gas is often pictured as composed of particles. In drawings, particles are usually pictured as tiny dots.

Task 1. Using dots, make a picture of the air in the flask in drawing A (above left), as it was before the pump was connected and used.

Task 2. Using dots, make a picture of the air remaining in the flask in drawing C (above, right) as it is after some air was removed by using the pump.

In the flask to the left, draw what you think your students will draw for drawing C (as it is after some air was removed by using the pump)?

How would you address this in your teaching?”
6. The Task shown below was given to a number of students.

The following diagram represents a cross-sectional area of a rigid steel tank filled with hydrogen gas. The dots represent the distribution of all the hydrogen molecules in the tank.

In the circle to the left, draw what you think your students will draw for one probable distribution of molecules of hydrogen gas in the sealed steel tank if the temperature is lowered.

How would you address this in your teaching?
Appendix C

First interview

Interview 1: Participants will be given the “Teachers’ Conceptual Understanding of the Gas Laws” assessment prior to the interview. Participants will be asked the following questions during the first interview conducted in May 2009.

**Part A**

1. Demographic information including degree held, teaching experiences, courses taught, information about the school.

Name:

Email/Phone:

Address:

Degree(s)/when: Years in teaching:

School:

Subject taught this year:

Subject taught in the past:

Level/courses of chemistry taught: Years of teaching those levels/courses:

School location: urban, suburban, rural Public/private/charter

Class sizes for actual classes taught this year:

Diversity/Student Population
2. As participants work through each problem on the “Teachers’ Conceptual Understanding of the Gas Laws”, they are to do so orally. Follow up questions for each problem is on the assessment.

3. Let’s talk about #2 scenario, the air pump.
   a. Would you use this in class? Why?
   b. How would you use this in class?
   c. What (representation) would you emphasize as the take home message in class?

4. Let’s talk about #3 scenario, the oil plugged glass tube.
   a. Would you use this in class? Why?
   b. How would you use this in class?
   c. What (representation) would you emphasize as the take home message in class?
Part B

3. The Tasks shown below were given to a number of students.

Read the story in drawings A, B and C above. As you may know, a gas is often pictured as composed of particles. In drawings, particles are usually pictured as tiny dots.

Task 1. Using dots, make a picture of the air in the flask in drawing A (above left), as it was before the pump was connected and used.

Task 2. Using dots, make a picture of the air remaining in the flask in drawing C (above, right) as it is after some air was removed by using the pump.

In the flask to the left, draw what you think your students will draw for drawing C (as it is after some air was removed by using the pump)?

How would you address this in your teaching?
4. The Task shown below was given to a number of students.

The following diagram represents a cross-sectional area of a rigid steel tank filled with hydrogen gas. The dots represent the distribution of all the hydrogen molecules in the tank.

In the circle to the left, draw what you think your students will draw for one probably distribution of molecules of hydrogen gas in the sealed steel tank if the temperature is lowered.

How would you address this in your teaching?
## Appendix D

### Ideal Responses & Targeted Chemistry Concepts for Subject Matter Knowledge for Teaching Assessment

<table>
<thead>
<tr>
<th>Item</th>
<th>Targeted Chemistry Concept</th>
<th>Ideal Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Kinetic Molecular Theory</td>
<td>Drawings or descriptions would include: equal molecules or moles of oxygen and carbon dioxide. Molecules moving in constant motion; Molecules are moving in random motion. Molecules colliding with one another and sides of container to create pressure. Molecules would take up the entire space of the container; There would be even distribution of O\textsubscript{2} and CO\textsubscript{2} in container. Drawings or descriptions would include: equal molecules or moles of oxygen and carbon dioxide. Molecules moving in constant, random motion. Molecules would take up the entire space of the container. There would be even distribution of O\textsubscript{2} and CO\textsubscript{2} in container. Average KE increase due to increase in temp. More Pressure exerted on sides of container due to more KE of each molecule;</td>
</tr>
<tr>
<td>1b</td>
<td>Kinetic Molecular Theory</td>
<td>Level of oil in glass tube will rise.</td>
</tr>
<tr>
<td>2a</td>
<td>Identifying Pressure and volume differences</td>
<td>After: 1. More air molecules are added to the reservoir thus, more molecules mean more collisions, which means more pressure exerted on the oil in the reservoir. 2. More pressure on the oil in the reservoir means that the level of the oil in the reservoir will drop thus forcing the oil in the glass tube to raise putting more pressure on the trapped air and decreasing the air’s volume in the glass tube. 3. At some point, the pressure from the added molecules in the reservoir will equalize with the pressure from the collisions of the air molecules trapped in the glass tube. 4. At this point, Boyle’s law can be applied to the air trapped in the glass tube. However, Boyle’s Law DOES NOT apply to the air trapped in the reservoir because as air is added (a change in number of molecules), the pressure on the oil is increased due to increased collisions between air molecules in the reservoir. This increase in pressure on the oil actually causes the oil level to drop, thus INCREASING the volume of space for the air molecules in the reservoir.</td>
</tr>
<tr>
<td>2b</td>
<td>Applying Boyle’s</td>
<td>Collect (read the pressure gauge) the pressure for the</td>
</tr>
</tbody>
</table>
### 2d. Law

Starting amount of air in the reservoir and the volume (read off the scale) of the trapped air in the glass tube for that pressure. Add air to the reservoir, and collect (read the pressure gauge) the pressure for this new amount of air in the reservoir. At this point, can use Boyle's Law to calculate the new volume OR read the new volume of the trapped air in the glass tube for that new pressure off of the scale.

At some point the pressure has to equalize between the air in the reservoir and the air trapped in the glass tube. Plot pressure on y-axis and volume on x-axis. Should see a power-inverse curve indicating as pressure increases, the volume will decrease.

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### 2e. Applying Boyle’s Law

![Boyle's Law Graph](image)

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### 3a. Predicting gas volume change

The oil plug will move towards the flask.

There is a certain amount of air molecules in the closed system of the flask and glass tube. The molecules in the system are in constant random motion colliding with one another and the sides of the container and tubing. There is an average kinetic energy of the molecules. When the apparatus is taken to the low temperature environment, the air molecules in the system will show decreased average kinetic energy due to a lowered temperature. The lower kinetic energy of each molecule will result in less pressure being exerted through collisions with other molecules and the container and tubing. Less pressure will also be exerted on the oil plug. Thus, the greater pressure on the outside of the oil plug will “push” the oil plug towards the flask. At some point, the pressure outside of the oil plug will equalize with the pressure inside the flask apparatus due to collisions between the air molecules and the container. Once the pressure is equalized, the pressure is constant and now volume of the air trapped inside the flask will decrease as temperature decreases according to Charles’ Law.

### 3b. Applying Charles’ Law
Mark a scale on or behind the glass tubing and use the change in the distance of the oil drop as a proxy for volume. Measure the temperature of the system at room temperature and note the location of the oil drop. Measure the temperature of the system at 120°C and then using Charles’ Law, calculate the new location of the oil drop. OR, using temperature and oil drop location for room temperature and the cold temperature as data points, graph the data and use the line to extrapolate the oil drop location for 120°C.

Plot temperature on the x-axis and volume (or distance of drop) on y-axis. Should see a straight line increasing.
Appendix E

Rubric for Written Assessment

<table>
<thead>
<tr>
<th>Item</th>
<th>Gas Law Concept</th>
<th>Representation</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Identifying pressure differences</td>
<td>Macroscopic</td>
<td></td>
</tr>
<tr>
<td>1b</td>
<td>Identifying the closed system</td>
<td>Macroscopic</td>
<td></td>
</tr>
<tr>
<td>1c</td>
<td>Applying Boyle’s Law</td>
<td>Particulate</td>
<td></td>
</tr>
<tr>
<td>1d</td>
<td>Applying Boyle’s Law</td>
<td>Symbolic</td>
<td></td>
</tr>
<tr>
<td>1e</td>
<td>Applying Boyle’s Law</td>
<td>Graphic</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Applying Boyle’s Law</td>
<td>Particulate</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>Predicting gas volume change</td>
<td>Macroscopic</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>Applying Charles’ Law</td>
<td>Particulate</td>
<td></td>
</tr>
<tr>
<td>3c</td>
<td>Applying Charles’ Law</td>
<td>Symbolic</td>
<td></td>
</tr>
<tr>
<td>3d</td>
<td>Applying Charles’ Law</td>
<td>Graphic</td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>Drawing molecular model</td>
<td>Particulate</td>
<td></td>
</tr>
<tr>
<td>4b</td>
<td>Drawing molecular movement</td>
<td>Particulate</td>
<td></td>
</tr>
</tbody>
</table>

0 = no explanation, explanations with irrelevant statements, and alternate conceptions
1 = partial alternate conceptions but indicate some degree of relevance toward the target concept
2 = sound arguments but minor mistakes toward the target concept
3 = answers with correct statements and use of target concepts
Appendix F

Second interview

1. Describe how you teach your unit on the gas laws?
   a. What concepts do you teach?
   b. What activities do you do?
   c. What drawings, models and/or analogies do you use during the unit?
   d. Do you do any demonstration(s)? If so, what demonstration(s) do you do?
   e. What are students doing during the demonstrations?
   f. Do you have students do any experiments? If so, what experiments do you have students do?
   g. What are students doing during the experiments?
   h. What assessments do you use to assess student learning?
   i. What sort of prior knowledge or understanding do you think students have regarding the gas laws?
   j. How do you take into account student prior knowledge and conceptions of the gas laws?